OULUN YLIOPISTO

FACULTY OF TECHNOLOGY

Topology optimization capability creation in R&D and product maintenance for mechanic parts

Juho Arpi

Industrial Engineering and Management

Master's thesis

January 2019

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TIIVISTELMÄ OPINNÄYTETYÖSTÄ Oulun yliopisto Teknillinen tiedekunta

Koulutusohjelma	Pääaineopintojen ala
Tuotantotalouden koulutusohjelma	

Tekijä	Työn ohjaaja yliopistolla
Juho Arpi	Osmo Kauppila, Petteri Annunen

Työn nimi
Topology optimization capability creation in R&D and product maintenance for mechanic parts

Opintosuunta	Työn laji	Aika	Sivumäärä
	Diplomityö	Joulukuu 2019	95s.

Tiivistelmä

Työn tavoitteena oli tutkia miten topologia optimointia voi hyödyntää mahdollisimman tehokkaasti tuotteiden ylläpidossa sekä tuotekehityksessä. Työssä on neljä osaa; topologia optimoinnin ja tuotekehityksen teoria, demo projekti tuotteiden ylläpitoon, demo projekti tuotekehitykseen ja implementointi ehdotus.
Työn alussa käyn lyhyesti läpi topologia optimoinnin sekä tuotekehityksen teoriaa. Seuraavaksi esittelen erään vanhan tuotteen kehityksen ja luon kyseisestä osasta topologia optimoinnin avulla uuden version. Samalla esittelen luomani prosessikaavion tuotteiden ylläpidolle, eli olemassa olevien osien optimointiin. Prosessikaavion idea on kertoa missä vaiheessa topologia optimointia tulisi hyödyntää. Esittelen myös taloudellisen hyödyn, joka voidaan saavuttaa hyödyntämällä topologia optimointia tuotteen suunnittelussa.
Seuraavaksi esittelen tuotekehitykselle luomani prosessikaavion uusien mekaniikka osien suunnittelulle. Osana työtä luon täysin uuden tuotteen ja esittelen prosessin tuotteen luomiselle. Lopuksi esittelen lopullisen tuotteen.
Työn loppuosassa kerään yhteen tutkimuksen tulokset ja pohdinnassa kerron oman näkemykseni topologia optimoinnin hyödyllisyydestä ja käytöstä.
Työn tuloksiin kuuluu prosessikaaviot tuotteiden ylläpitoon sekä tuotekehitykseen, kaksi topologia optimoinnin avulla suunniteltua tuotetta ja laskut miten paljon topologia optimoinnin hyödyntämisellä on mahdollista säästää sekä implementointi ehdotus.
Työn tutkimusmenetelmä on tapaustutkimus, mutta tuloksia on mahdollista hyödyntää kaikissa yrityksissä missä suunnitellaan mekaanisia osia ja täten tulosten yleistettävyys on hyvä

Muita tietoja

ABSTRACT FOR THESIS

University of Oulu Faculty of Technology

Degree Programme	Major Subject
Industrial Engineering and Management	

Author	Thesis Supervisor
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Topology optimization capability creation in R&D and product maintenance mechanic parts

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Abstract

The goal of this thesis is to research and find out how to use topology optimization effectively in product maintenance and product development. The thesis consists of four main parts: theory for topology optimization and product development, a demo project for product maintenance, a demo for product development and implementation suggestions.

At the beginning I go through topology optimization and product development theory, but only briefly, since the goal is not to go too deep on how topology optimization works but rather on how to benefit from it. Next, I present an old product and how it has been developed throughout the years and then describe how it could have been done with topology optimization and how much resources could have been saved by doing so. As a part of this work, I designed a new version of that part by utilizing a process chart I created for product maintenance.

Then I present the process chart I created for developing new mechanical parts for product development, and show how I created a completely new product following the presented process chart.

At the end of this work I summarize my findings and give suggestions on how to start using topology optimization most effectively.

Results include:

- Process chart for product maintenance and product development
- Two parts designed with topology optimization
- Calculations on how much resources could be saved with topology optimization
- Short implementation plan suggestion

The research method for this thesis is case study, but these results can be used by any corporation that designs mechanical parts and therefore results are well generalizable.

Additional Information

TABLE OF CONTENTS

MARKINGS AND ABBREVIATIONS

AM	Additive Manufacturing
CAD	Computer Aided Design
DFT	Design Fine Tuning
DV	Design Validation
PM	Product Maintenance
R&D	Research and Development
TCO	Total Cost of Ownership
TO	Topology Optimization

1 INTRODUCTION

Product development as a whole is going through a change as products are becoming increasingly complicated and complex with more and more demanding requirements, for example, regarding product usability and quality. This, coupled with the fact that global competition drives prices down now more than ever, makes it clear that new tools are needed to maximize product development efficiency. (Dallasega et al. 2016)

Complex products mean longer lead times and even more expensive R&D and Product development processes (Dallasega et al. 2016). When developing, for example, weight bearing parts it is common to aim for the most efficient shape/structure. During the last decades, the application of structural optimization has progressed so much that it is now available in many software packages. For example, when designing structural elements, TO can be used to optimize the process as well as the product or part (Schramm & Zhou 2006). Digitalization has also risen to be one of the key factors in everything, from simple part development to large scale multi-discipline design and development projects. As the cost of these projects rise, it is important to try and make the process as lean as possible. Basically, this means cutting costs and lead time wherever possible. The cost of the process will affect the price of the final product, and therefore optimizing the process is as important as optimizing the product. An optimized product can be achieved by optimizing the parts it contains. Topology optimization seems to be just the right tool when trying to optimize the development process and the actual product to achieve the lowest possible TCO. This leads to the purpose of this research: to investigate the advantages of utilizing topology optimization in making quality products with optimized geometry and process.

The research questions are:

RQ 1. How can topology optimization be applied to PM?

RQ 2. How can TO be applied to R&D?

First research question will be studied through a demo part that is currently in the maintenance phase of its lifecycle. The idea is to make a new version of that product with the help of TO and a new product development flow I created for PM. Then I will calculate how much resources the new version could save if it were implemented now and if it had been implemented when the first casted version was created.

The second research question will be studied by creating a totally new product with set requirements by utilizing TO and the product development flow I created for R&D projects.

The results will include process flow charts for PM and R&D, calculations of how much could be saved by utilizing the recommended process flow, including TO, two fully designed products that were created by following recommended process flows and an implementation plan. The R&D product will also be manufactured and tested to see if the process really works.

This thesis is structured as follows: in chapter 2 the principles of TO and PD are introduced. Chapter 3 briefly outlines of the main TO software options. Chapter 4 includes pilot study and detailed description on how demo product was developed for product maintenance. Chapter 5 focuses on the process of creating totally new product. Chapter 6 is dedicated to “lessons learned” from pilot studies and it is followed by chapter 7 that contains results collected from the pilot studies. Chapter 8 is dedicated to summary and discussion including some ideas for further research.

2 BACKGROUND

In this section we will briefly review the most essential theory regarding TO and NPD. This will be rather brief since the focus of this thesis is not on the algorithms or how TO is calculated, but rather on its benefits.

2.1 Topology optimization

There are three different categories for optimizing structure: sizing optimization, shape optimization and topology optimization. (Fig. 1) To put it simply, topology optimization (TO) is a mathematical way of optimizing structure to obtain as much structural integrity as possible with the desired amount of weight/volume. The idea is to distribute material within a specified region to create a structure as efficiently as possible. For this to work one must provide loads, support conditions and the volume that can be used. (Gunwant & Misra 2012, Bendsoe & Sigmund 2003)

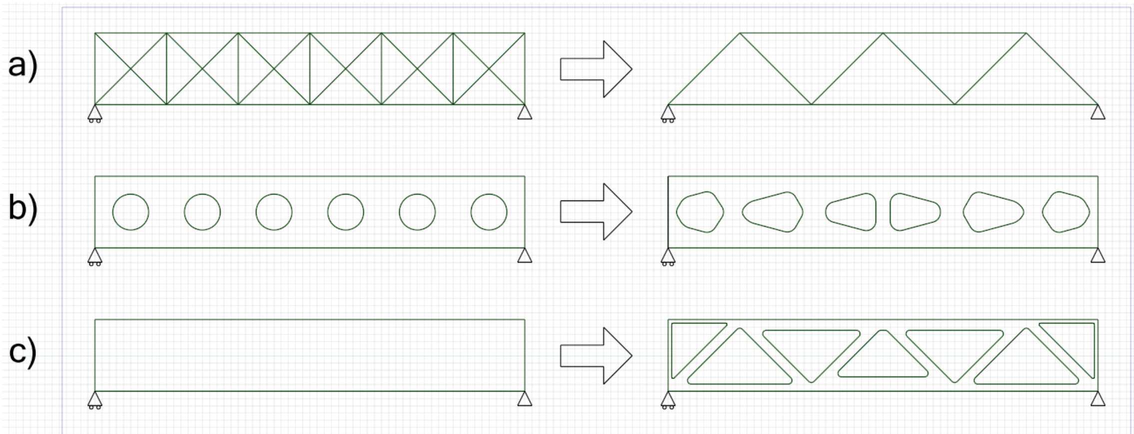


Figure 1. Different categories of structural optimization. On the left is the starting point and on right is the result of optimization. a) Sizing optimization b) Shape optimization c) Topology optimization. Modified from Bendsoe & Sigmund 2003.

A common way of performing Topology Optimization is to aim for minimizing compliance. Compliance means the work a force or a load does on the structure. Less compliance means less work done to the structure, which means less energy is stored in the structure. This will lead to the structure being stiffer (Gunwant & Misra 2012). In other words, minimum compliance means finding maximum global stiffness through the whole structure. Finding minimal compliance is a gradient-based method and it doesn't provide discrete results (Gunwant & Misra 2012, Bendsoe & Sigmund 2003).

Mathematically compliance is following:

$$Compliance = \int_V fudV + \int_S tudS + \sum_t^n Fiu$$

Where:

u = Displacement field

f = Distributed body force (Gravity etc.)

F_i = Point load on i^{th} node

u_i = i^{th} displacement degree of freedom

i = Traction force

S = Surface area of continuum

V = Volume of continuum

Together with the minimum compliance approach it is common to use the SIMP method, which stands for Solid Isotropic Material with Penalization. SIMP is used to create topology which is closer to the desired 0-1 topology. 0-1 refers to the density of each element where 0 stands for void or no material and 1 stands for material. Without using, for example, SIMP, the result of topology optimization would not be discrete but rather continuous. (Gunwant & Misra 2012, Bendsoe & Sigmund 2003)

The SIMP method is used by giving each finite element, formed for example by meshing, an additional property of pseudo density Xj, where Xj is somewhere between 0 and 1. Pseudo density alters the stiffness of the material (Gunwant & Misra 2012). The formula is:

$$xj = \frac{\rho j}{\rho 0}$$

Where:

ρj = Density of the j^{th} element

ρ0 = Density of the base material

xj = Pseudo-density of the j^{th} element

The pseudo density of the finite element works as a design variable when performing topology optimization. The stiffness of the j^{th}. element Kj depends on its pseudo density as below.

$$Kj = Xjp\ K0$$

Where:

K0 = Stiffness of the base material

p > 1 = Penalization power

Usually p = 3. Thus, when Xj = 0, Ko = 0, and when Xj = 1, Ko = 1. Ko = 0 means that there is no material and Ko = 1 means that there is material (Gunwant & Misra 2012). Basically, SIMP makes it uneconomical to have density values that differ from 1 or 0 and therefore it steers the topology to be more discreet rather than continuous.

In addition to SIMP, other filters are also used to create a desired solution. One reason for this is the fact that topology optimization suffers from some numerical issues that often lead to an effect called checkerboarding. In 1997 Sigmund presented a filter that can diminish the checkerboard effect. The filter takes one element and then calculates the weighted average of its eight adjacent elements. Then the nodal sensitivity is distributed back to the originally chosen element as the average of the surrounding elements. (Sigmund 1997) Below is an example of the checkerboarding effect with different element quantities (mesh size).

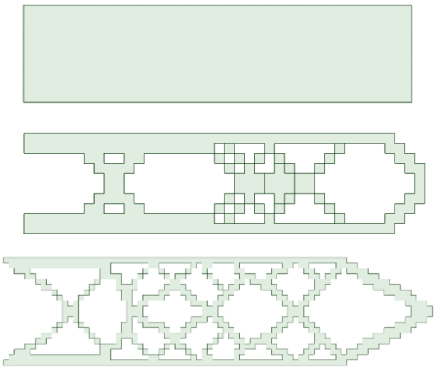


Figure 2. Checkerboard problem for cantilever beam, simplified picture for clarity. A is on top, B in the middle and C at the bottom A) Initial design, B) solution for some hundreds of elements, C) solution for some thousands of elements. Modified from Bendsoe & Sigmund 2003.

In addition to the SIMP method, topology optimization software often use the Sequential Convex Programming and Optimality Criteria methods to further affect the output. Sequential Convex programming is used to prove global convergence and to stabilize the algorithm (Ni et al. 2005). Optimality Criteria is an iterative solver that is used with simpler optimization problems, as it can optimize simple energy functional with a single constraint on material (Yang & Yin 2001).

Different topology optimizing software use different filters and solvers, but those mentioned above are the most common ones, for example Ansys uses these and it is the standard company in this field.

2.2 Advantages of topology optimization

2.2.1 Design advantages

Normally when designing a product, the engineer creates the final design through trial and error. This process is time consuming and cumbersome and it requires constant attention and active work. With Topology optimization technology, the design process can be changed to a process that is driven by computational analysis. This means that the analysis would define the best possible design straight away. Even though the optimization calculation might take a while, it doesn't require constant attention or any active work. Therefore, the designer engineer can perform other tasks while the optimization software is running. (Schramm & Zhou 2006)

2.2.2 Cost advantages

Many industries that are sensitive to any extra weight, such as automotive and aerospace, have already been using topology optimization for a while as a tool to reduce as much weight from their products as possible without compromising structural integrity. These industries were first to implement topology optimization since every extra Kg carried from point A to B means extra costs. (Krog et al. 2002)

Decreasing the weight of a product or a part has a wide influence on its TCO, as decreasing weight means less raw material and less logistics costs. To mass produced mechanical products, these two are the biggest influences on TCO.

Topology optimization has an effect on the design process, as was discussed before. With TO it's possible to reach the optimal structure with just one iteration instead of, for example, ten. It is clear that when the design process is shorter, the NPD process costs less, but the biggest cost saving in products' NPD phase comes from having to order and test fewer prototypes. Especially if the used prototypes need to be machined. Of course TO does not altogether remove protype testing from the NPD process but it is reasonable to think that with TO you can have fewer protypes to find the desired solution that meets the strength requirements. (Schramm & Zhou 2006)

With TO combined with AM it is also possible to attain designs that contain fewer separate parts. This is quite important in product portfolio management. In larger companies, PDM is often handled with various software and maintaining each part in the system has a cost attached to it. In addition to that, from a purely management point of view it is better to have fewer products in your portfolio, if it is possible without compromising quality or functionality.

Potential cost saving listed below for clarity:

- Less material = Less raw material costs

- Less weight = Less logistics costs, better usability

- Fewer parts = Less logistics costs, better usability, better quality

- Fewer design loops = Less R&D costs, faster lead time

- Rapid prototyping = Faster testing, on site printing

- New material = For example longer lifetime for mold (more than 10x)

- More cavities per one tool = Less tooling cost

2.3 Manufacturing processes

Relevant manufacturing processes for this subject are:

- Casting
- Machining
- Extrusion
- AM

Different manufacturing styles have different limitations and therefore different requirements when it comes to TO.

2.3.1 Casting

Casting is a process wherein molten metal/plastic/composite is injected to a mold. The benefit of casting is its speed after the process has been optimized and tuned. Casting is also a relatively cheap way to produce products/parts. Casting has its restrictions, as it is not possible to create geometries that include pockets, overhangs or too thin a wall/features. Also, creating large parts requires immerse amount of pressure which can be problematic. Casted parts must have a lip relief angle, otherwise you cannot remove the casted part from the mold. (Campbell 2011, Nykänen 2007, Atanasova 2007)

All the restrictions have effects on the design. For example, TO solutions without constraints is not a castable part.

2.3.2 Machining

The machining process starts with a block of material from which material is removed to attain the desired result. Machining is a rather expansive process and it produces a lot of waste. CNC machines can be incredible precise: they can perform movements as small as 0,00254mm. The possibility of creating complex geometry depends on the amount of axis the machine has; more axis of movement means possibility for more complex geometry. Machining has quite a few restrictions, as for example hollow features are not possible. Machining is a somewhat slow and expensive process, therefore it is often used, for example, with casting to smoothen the surfaces and to create smaller features. (Overby 2010)

2.3.3 Extrusion

Extrusion is a process where a billet (a block of material) is passed through a die. It’s suitable for products that have a fixed cross section. Shapes that extrusion can provide are very simple. Extrusion provides parts that are uniform and therefore quite resilient. As a process, extrusion is not as expensive or slow as machining but is more expensive and slower that casting. (Giles et al. 2013)

2.3.4 Additive Manufacturing (AM)

Additive manufacturing is the newest production method of all those mentioned thus far. AM has developed alongside with CAD/CAE systems. The potential of TO can be realized best by using AM since it basically does not have any restrictions regarding geometry. The constraint on minimum member size depends on materials and technology that are used. (Gibson et al. 2014)

AM covers many different methods of manufacturing, but the ISO AM terminology standard describes it as follows:

> "Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (ISO/ASTM 52900:2015)

The only restriction for AM is overhang, meaning structures that have an overhang angle over the threshold must be supported. The angle threshold differs depending on the material and technology. If a structure has overhangs it does not prevent its manufacturing, but they make it necessary to use post processing to remove the supports. This also makes AM less efficient since more material will be used than necessary. (Gibson et al. 2014, Hoffarth et al. 2017)

AM is growing fast, and it is the manufacturing method of the future. At the moment it is not used very widely for anything else than prototyping, because it is quite slow and expensive. (Hoffarth et al. 2017)

2.4 Product development process

Product development is defined as action that is aimed at creating new products or services and bringing them to market. Most companies use product development to retain a competitive edge on their competitors. Product development often aims to create sustainable growth and a strategic advantage for a company. (Lutters 2014)

At the very beginning, product development was organized into processes that followed one another, which is called the waterfall model. As we all know, waterfall model is extremely inflexible, and it only allows one task to be completed at a time. The waterfall model leads to long iteration rounds and it lacks communication between the processes, which in turn can lead to an undesired outcome. (Erickson 2015)

In the 80s, Robert G. Cooper developed the Stage-Gate system for product development. “Stage-Gate is a conceptual and operational roadmap for moving a new product project from idea to launch”, in Cooper’s own words. The idea is to manage NPD process to attain better results. The Stage-Gate model consists of stages and gates. Stages have, for example, activities, analysis and deliverables. The gate means the decision to either go on with the project or to kill it. Commonly NPD process has about five stages and gates. (Cooper 2008)

Nowadays, Stage-Gate model and other NPD related tools have been developed further. As a result, new tools and principles have emerged, such as Concurrent engineering and Design For Excellence (Bjanrnoe 2006). As an example, Stage-Gate model barely resembles its original version today (Cooper 2008).

Product development can be roughly divided in to two categories, continuous and discontinuous (Veryzerin 1998). Continuous refers to products that are not completely new but rather new versions (Veryzerin 1998). Discontinuous again refers to products that are completely new (Veryzerin 1998). There are also other ways to divide new product development. Trott (2012) presented six different categories: New to the World, New product lines, Additions to existing lines, Improvements and revisions to existing products, Cost reductions and repositioning. Veryzer (1998) states that product innovation can also be divided into four different categories (fig. 3)

<table>
<tr><td></td><td></td><td colspan="2">Product capabilities</td></tr>
<tr><td></td><td></td><td>Same</td><td>Improved</td></tr>
<tr><td rowspan="2">Technological capabilities</td><td>Same</td><td>Continuous</td><td>Commercially Discontinuous</td></tr>
<tr><td>Advanced</td><td>Technologically discontinuous</td><td>Technologically and Commercially Discontinuous</td></tr>
</table>

Figure 3. Product Innovation categories (Veryzer 1998)

It is important to know to which category a product development process belongs, since different categories require a different style of management and resources. For example, a simple cost reduction process does not require the same kind of planning and resources as developing totally new technology. (Veryzer 1998)

Product development has many different phases. Ulrich and Eppinger (2012) defined six phases for a generic NPD process:

1. Planning
2. Concept development
3. System-level design
4. Detail design
5. Testing and refinement

6. Production ramp-up

Each of these phases contains many activities. Activities differ to match the requirements of the product. Activities could be chosen, for example, by using the categories mentioned above. (Ulrich & Eppinger 2012)

Quite recently Lean has also been implemented for product development process. When implementing Lean onto NPD process, there are two main approaches: A Process approach and a Design approach. The Process approach focuses on the actual process steps and its intent is to improve the flow and reduce waste. The Design approach focuses on the actual design of the product and the point is to make the product design as lean as possible, for example by trying to design a product to be as modular as possible. Design approach can further be divided into two different approaches, one that focuses on creating a lean design process, and another that focuses on creating lean production. The tools for creating leaner NPD processes are Set-based design, Modularity, DFM and Concurrent engineering. (Bjarnoe 2006)

2.5 Topology optimization in mechanical product development

When developing mechanical products, often the starting point is requirement specification. It describes what the product must be able to withstand and what its functionalities must be. For example, the requirement spec could tell you that the new product/part must be able to carry a 10 Kg load 0,15 m away from a wall and that it must be able to be attached to a wall. In addition to that there could be requirements about corrosion or usability. After determining the maximum forces that the part/product will have to deal with, it is possible to start initial design. Topology optimization could come into use at this point, since it can help determine the best possible shape. With current TO software it is also possible to test different manufacturing styles. Below is a chart of a product design development process when using AM as the manufacturing style. (Rohde et al. 2018)

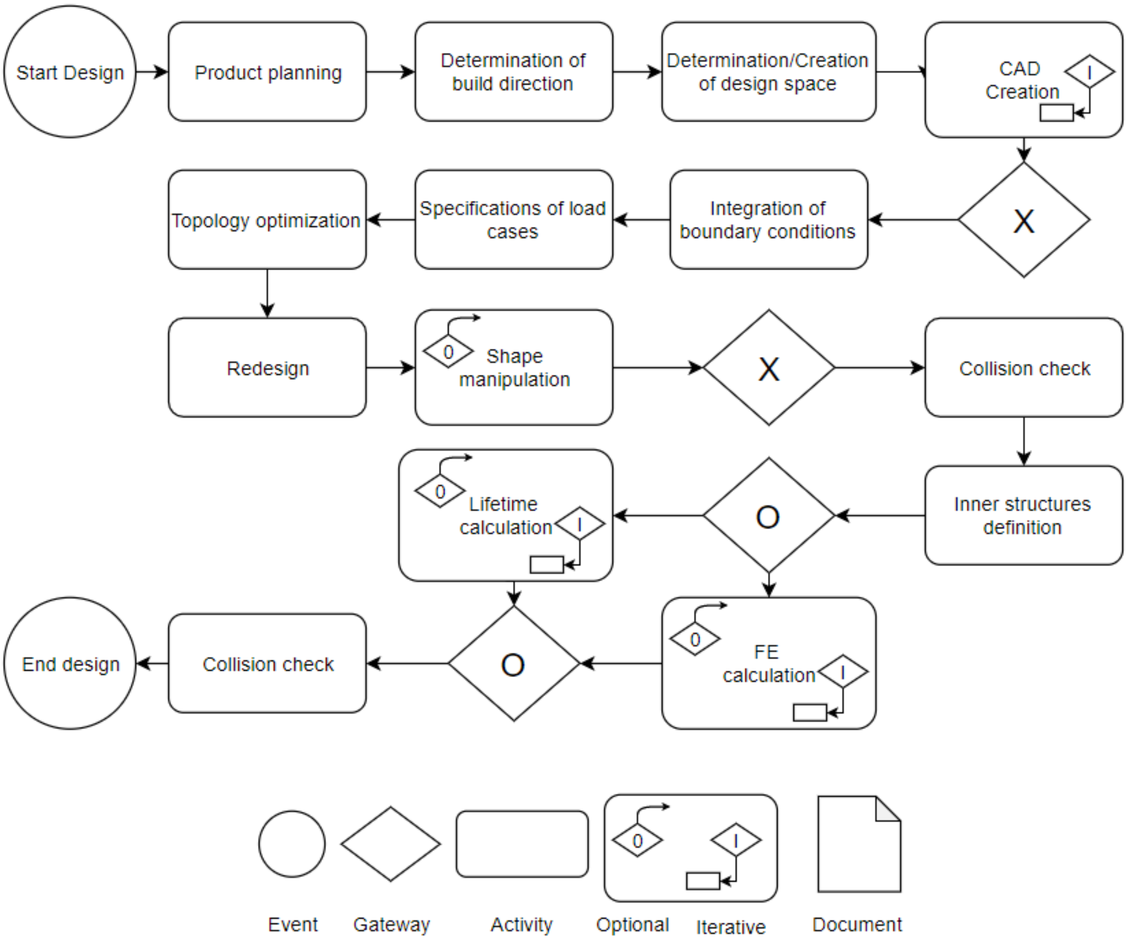


Figure 4. This design flow could be applied to any production method with slight changes. Modified from Rohde et al. 2018

3 CAPABILITIES OF TOPOLOGY OPTIMIZATION SOFTWARE

This thesis work is done using Ansys workbench version 19.1. The goal of this thesis work is not to give an opinion on which Topology Optimization software should be used. Almost all commercial Topology optimization software work similarly, and the biggest differences come from user-friendliness and interface.

Biggest operators in the TO field are MSC.Nastran, Genesis, OptiStruct, Ansys and Tosca.

There are a few different TO software, but they have few functional differences. Every software uses similar algorithms and filters. Most differences are in the user interface and the learning curve. Different software may also have, for example, different manufacturing constraints.

Common manufacturing constraints are:

- Symmetry
- Cyclic
- Min/max member size
- Casting with pull out direction
- Extrusion
- AM with print direction

Usually TO needs support points, loads, design space and material as an input to be able to find the optimal solution. To refine this solution, it is possible to use any constraint that was mentioned above. That way it is possible to make sure that the output of TO is manufacturable by the chosen method (casting etc.).

The output of TO is in the STL file format which is a facet file that only has surfaces. STL files cannot be modified by most CAD software, but for example Ansys Spaceclaim can modify STL files or to convert them to solid files. Output of TO is often very complex and it is not feasible to use it as such even though it is, in principle, possible. Because of this, the TO solution always needs some post processing to make it feasible for manufacturing. Some CAD software have automatic algorithms to smoothen the result. In this thesis work I will be using Ansys for TO.

An example of a simple TO problem (fig. 5-9): The first figure shows forces, supports and design space. The material is structure steel. The second figure show the result of initial static stresses analysis. The third figure show the result of TO, no manufacturing constraints were used. The response constraint was to retain 50% of original mass. The fourth figure shows the final design, which is a simplified version of the TO solution. The fifth figure shows the result of stress analysis for the final design.

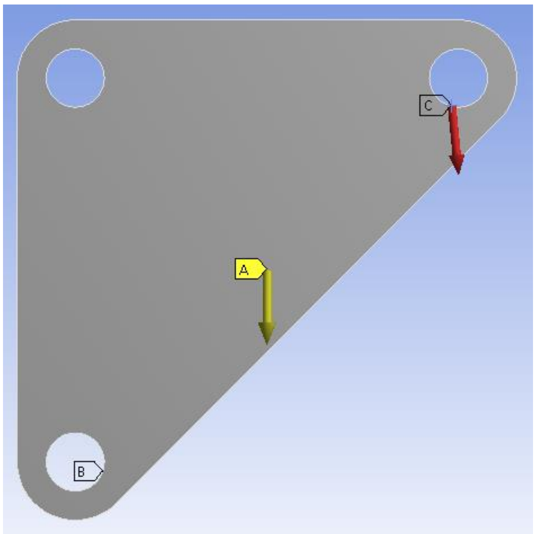


Figure 5.

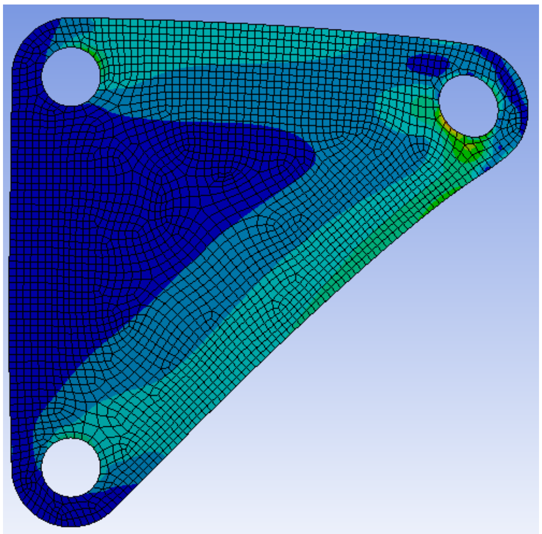


Figure 6.

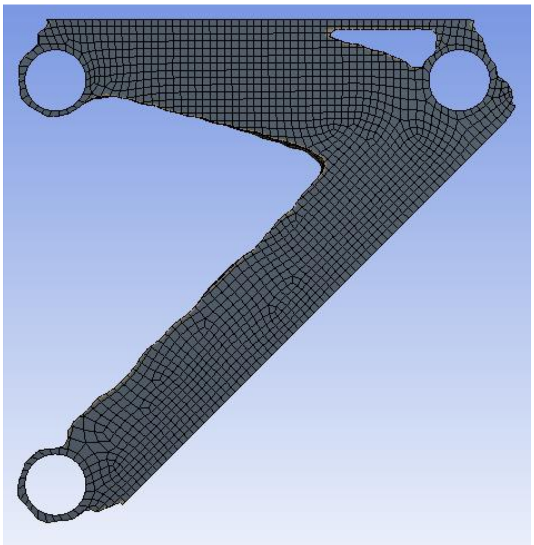


Figure 7.

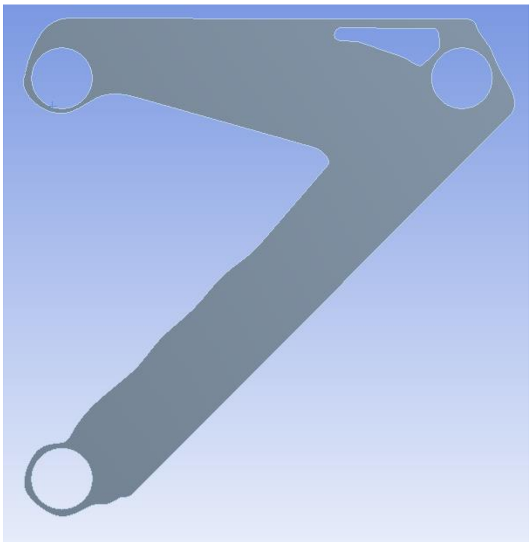


Figure 8.

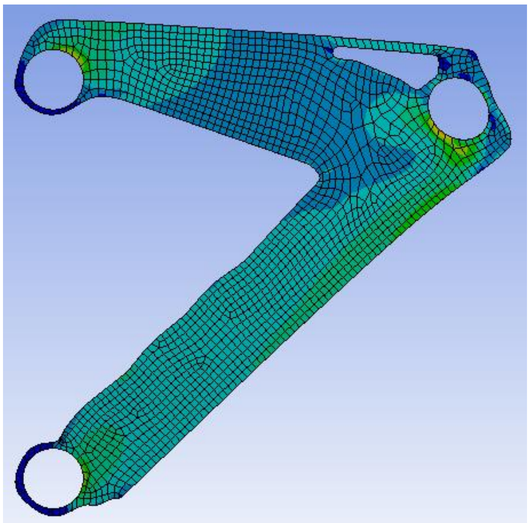
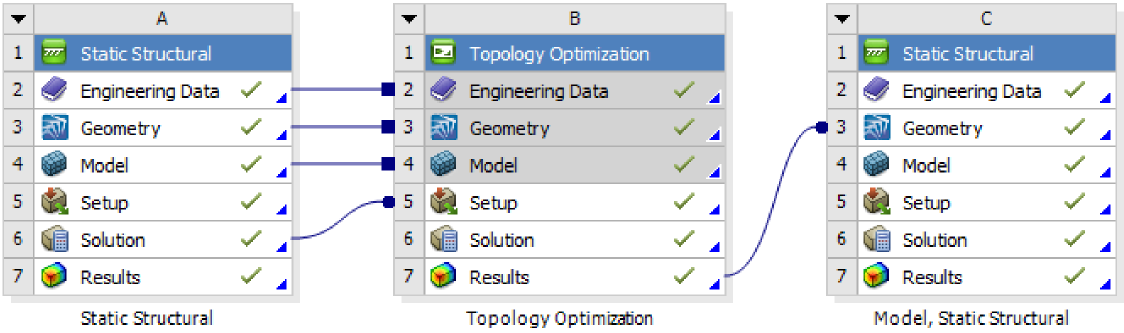


Figure 9.

The weight of the original part was 1411,7 g and max stress was 66,917 MPa, whereas the optimized weight is 721,52 g and max stress is 68,854 MPa. As the material is structural steel it is still not close to its limits even after optimizing. In this case it seems it would be possible to lessen the "weight to retain" percent.

In Ansys, the Topology optimization workflow at its simplest mode below.



A. Initial analysis B. Topology optimization C. Design validation

4 PRODUCT MAINTENANCE PILOT STUDY

In this study I will first broadly describe the development process of PRODUCT X, which is an example of how products are currently being designed, tested and verified. PRODUCT X refers to a product that is currently in maintenance phase of its lifecycle. Then I will go through the cost reduction/quality improvement process that I created for product maintenance.

This thesis contains two pilot studies one for product maintenance and one for product development (R&D), since these two differ from each other quite radically.

For the R&D study I will create a totally new product from scratch using the process flow I created for mechanical part development in R&D.

Information on how products have been designed/developed has been gathered from the engineers involved in the design of the product in question.

4.1 Development process of PRODUCT X

At Telecommunications firm where I did my thesis, mechanical product development starts from product management giving a task to R&D. The need for a product has surfaced so product management decides to start an NPD project. The project starts with feasibility studies and then moves on to the design phase. Currently the way projects are managed depends highly on the manager. At one point the aim was to move all projects, even mechanical ones, to the agile model, but my understanding is that this idea has never been fully implemented.

Typically, the task of designing a product is given to a mechanical engineer who then is responsible for ensuring that the product will be ready in time and that it will fulfill the requirements set for it.

Product requirements are often discussed in project meetings that may occur weekly or, for example, bi-weekly. Often requirements aren’t communicated clearly from the start and during the project new requirements may arise. This causes problems for designing a product since it may mean that the designing work must be started again from the beginning.

The actual design work is something the engineer does on his own and design review meetings will be held from time to time to get feedback and comments from other engineers and professionals. It is, naturally, common to use old products or design as a basis for the new design in the early concept phase. This does lead to the question of what if the original concept is not even close to being optimal? In that case a suboptimal design could persist simply because designers reuse old concepts and designs.

The design process is quite simple: The engineer makes a draft product, then simulates it, then changes the design and simulates it again. However, since simulating isn't yet something that every engineer is capable of, the models may go to another person for simulating and that further slows down the process.

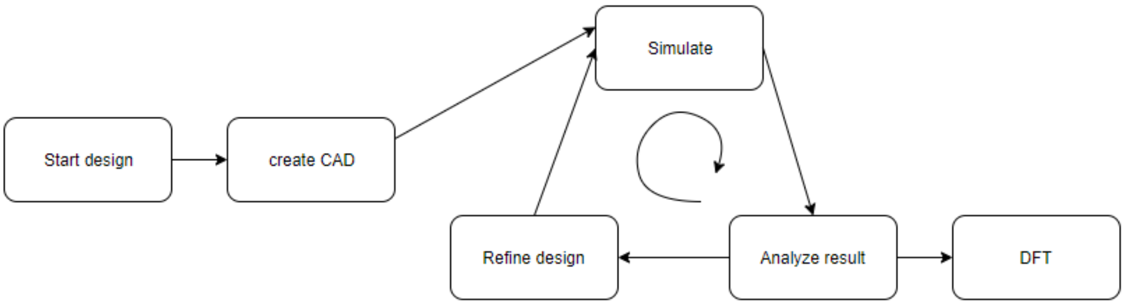


Figure 10. Process flow for clarifying the loop designer can get "stuck" with

Using this kind of flow, one will end up with a so-called manually optimized product. If the designer is very capable, the result may be good, but it will take multiple iterations and loops, which takes an unnecessarily long time. There is one significant risk in using this approach: what if the first design's geometry is totally off? If this happens, no amount of refining will give the most optimal geometry.

PRODUCT X was first released in 2006 and the first design was made of stainless steel. It was a sheet metal design that was made to handle all tests without difficulty. Forecasted volumes were small at the beginning and because of that, cost impact would be low no matter the design. Especially in that kind of a case the cost of verification must be considered; testing is mandatory but expensive and if more than one round is needed the cost of verification will multiply.

4.1.1 Evolution of PRODUCT X design

After the initial release in 2006, PRODUCT X's design has changed quite a bit to generate cost savings or to add features. Below is a set of figures that show all six different versions, including the sixth and latest, version number 206.

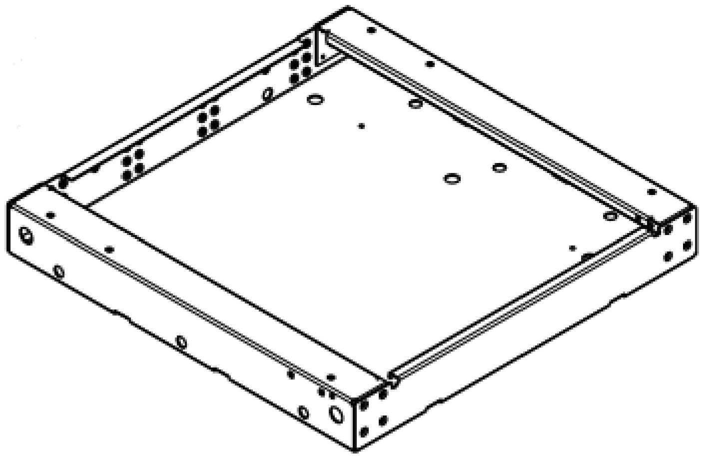


Figure 11. PRODUCT X version 101

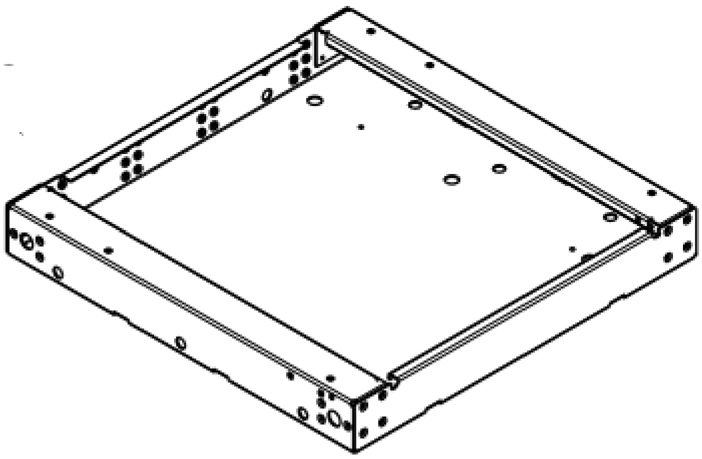


Figure 12. PRODUCT X versions 102

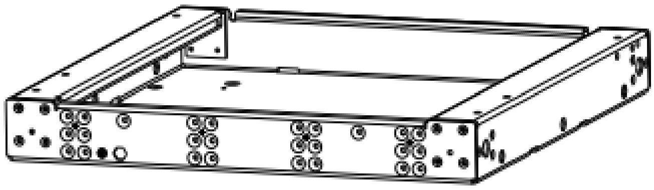


Figure 13. PRODUCT X version 103

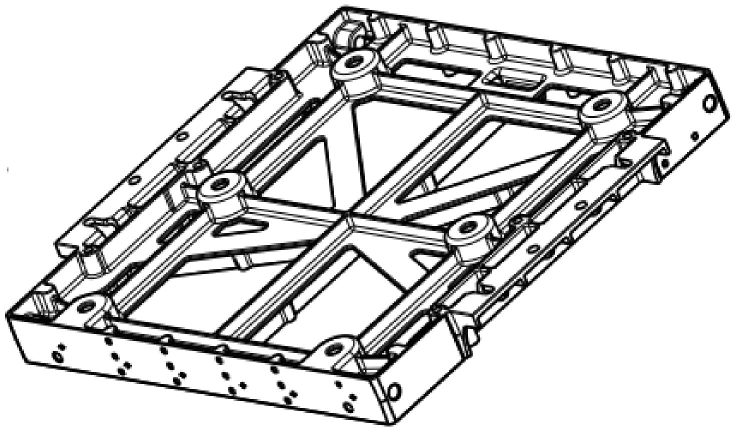


Figure 14. PRODUCT X version 104

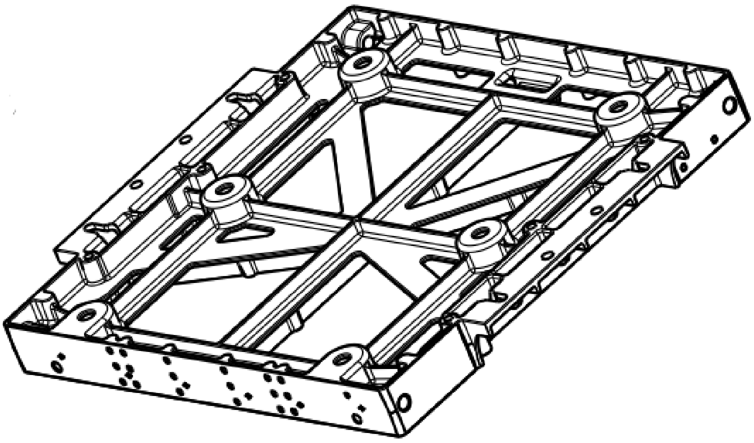


Figure 15. PRODUCT X version 105

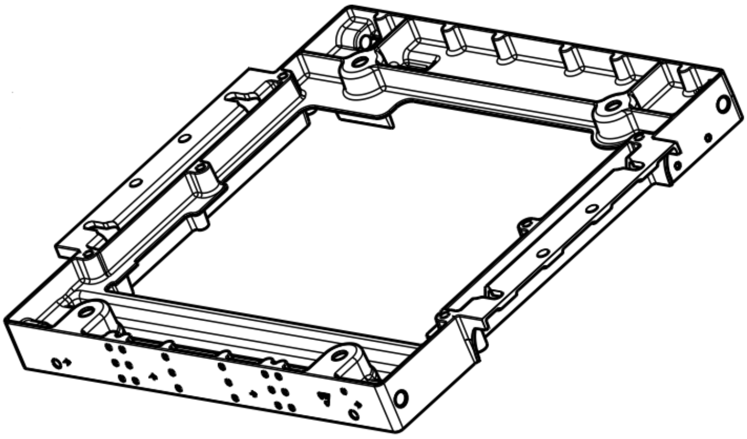


Figure 16. PRODUCT X version 206

First significant changes happened between versions 103 and 104. At that point material changed from stainless steel to aluminium alloy. After that product weight has been reduced a few times, finally resulting in the final product. Below is a table on when each version was released.

Version	Release year
101	2006
102	2006
103	2008
104	2009
105	2011
206	2012

Table 1. PRODUCT X version and release year

It took six years and numerous cost reduction projects to reach the current weight and price for the product. Below are charts that visualize how the weight, demand, composition and price of the product has changed during this time. Unfortunately, no data on yearly volumes or prices before the year 2012 is available. This is due to a system change.

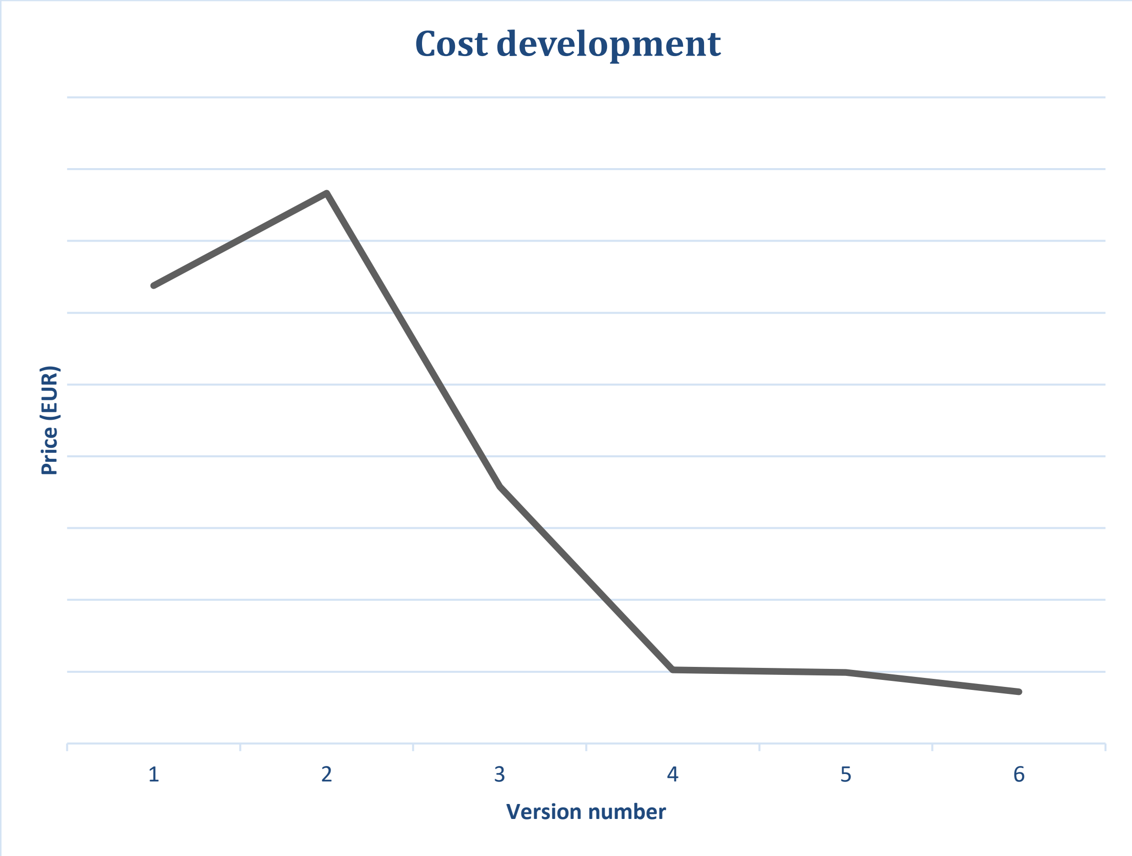


Chart 1. PRODUCT X cost development

The above chart shows how cost of the product has gone down more than 90% from the highest cost. Here it is easy to see that changing the material to aluminium alloy and the manufacturing method to casting and machining brought the cost down quite significantly from. Of course, the whole design changed at that point, as can be seen from the pictures of different versions above.

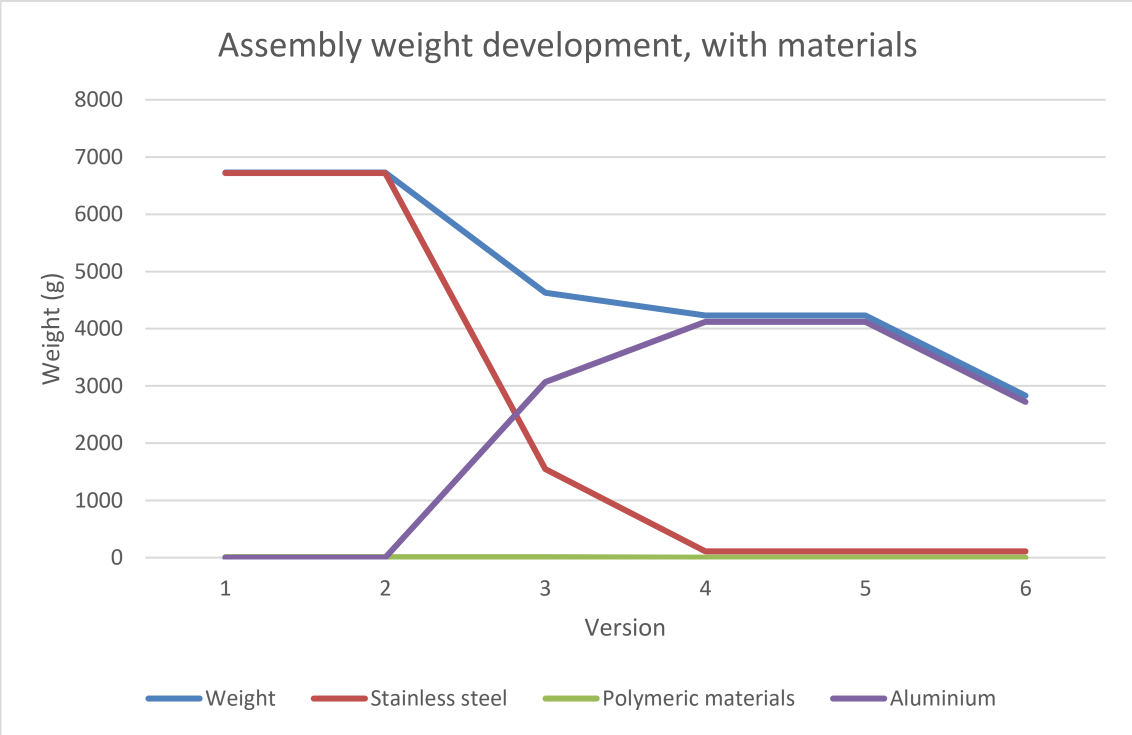


Chart 2. Assembly weight development and material usage

From this chart it can be seen exactly how much product weight has gone down during the years and how the usage of different materials has changed. The use of stainless steel dropped to almost zero when moving from sheet metal design to casting-plus-machining design. When comparing casting designs to each other it becomes clear that at that point the biggest influence on cost is the amount of raw material. In conclusion it is fair to say that if the design weight drops, for example, 20%, the cost of the product drops about 10%. Yearly volumes have an effect on this ratio, since the biggest cost driver for casted design is the cost of the mold. The chart below that shows this correlation more clearly.

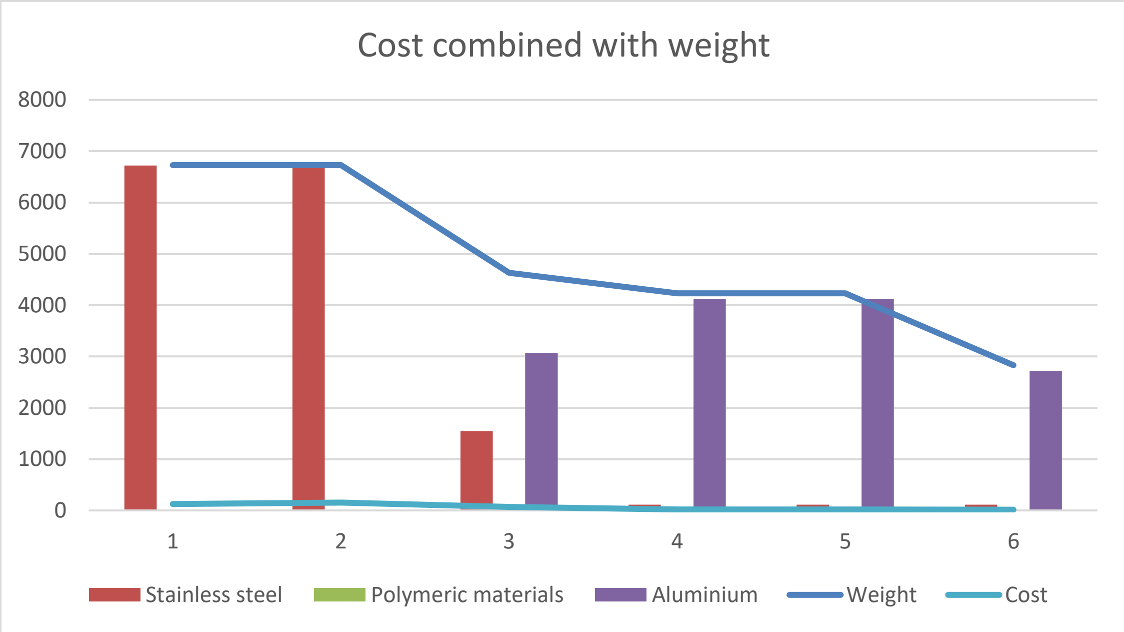


Chart 3. Cost development with weight development

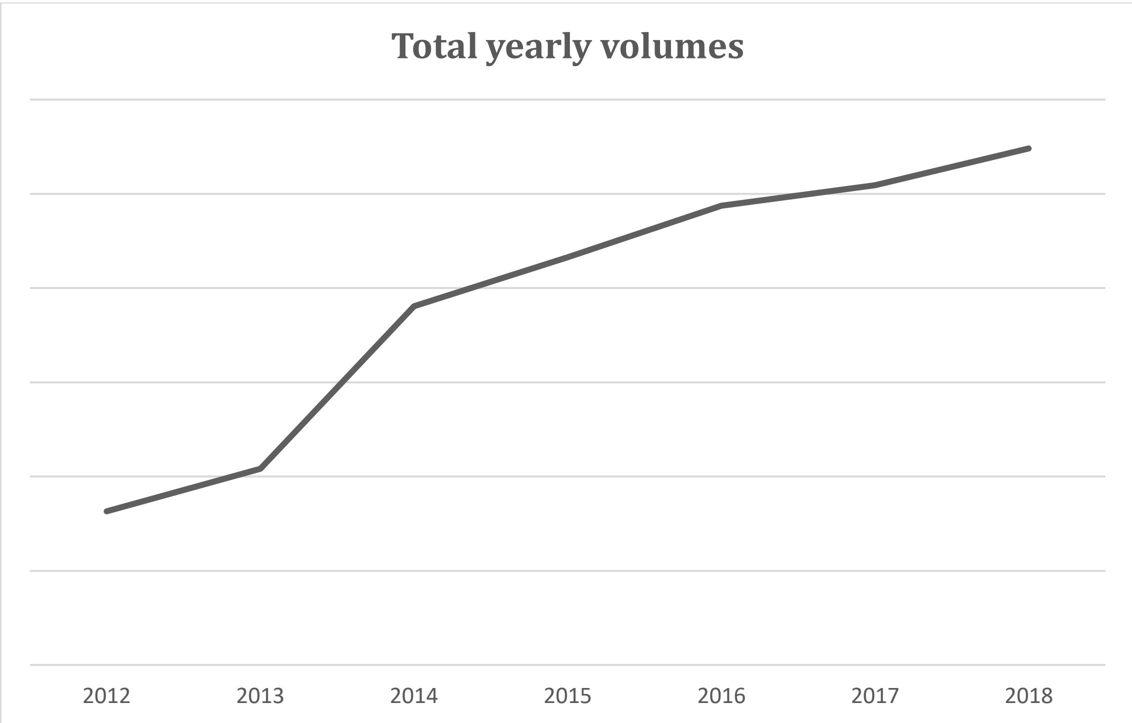


Chart 4. PRODUCT X yearly volumes

As the yearly volumes rose, motivation to lower the product's cost rose also. It is quite common at Telecommunications firm that products that have low forecasted volumes go through the development process without much attention to cost. This is understandable because if yearly volumes are low, even a significant drop on the product's cost doesn't bring much cost savings in a yearly scale. But when yearly volumes are high even a small cost reduction will cumulate into a significant cost saving. PRODUCT X is the perfect example of a case where the forecasted volumes were initially low but then rose very significantly. That is also why it was reasonable to start cost reduction projects for PRODUCT X.

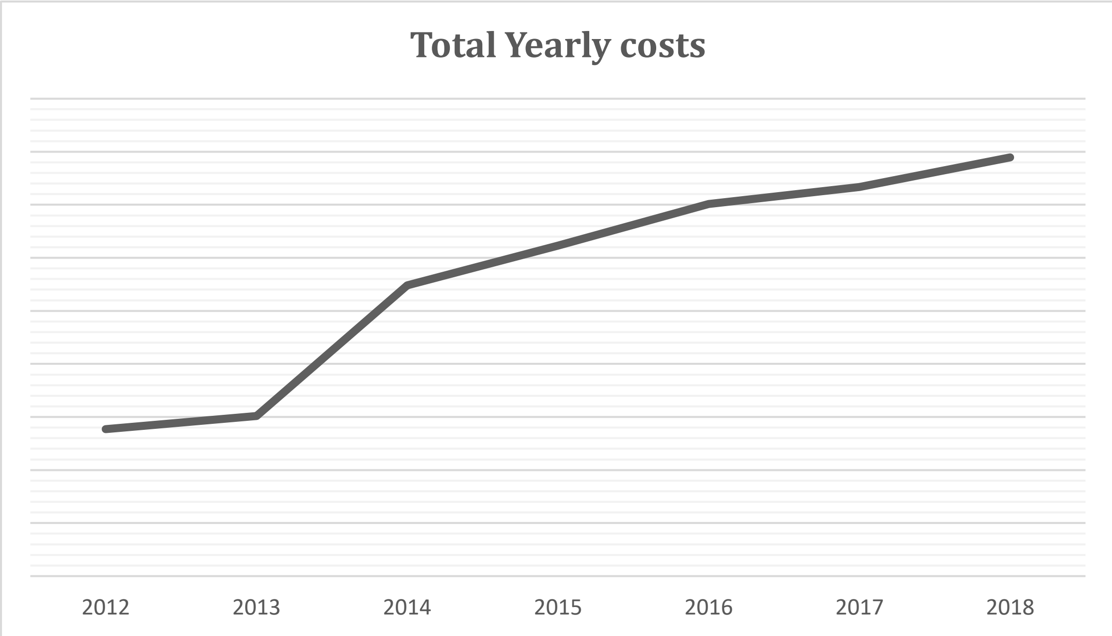


Chart 5. Total yearly costs accumulated by PRODUCT X

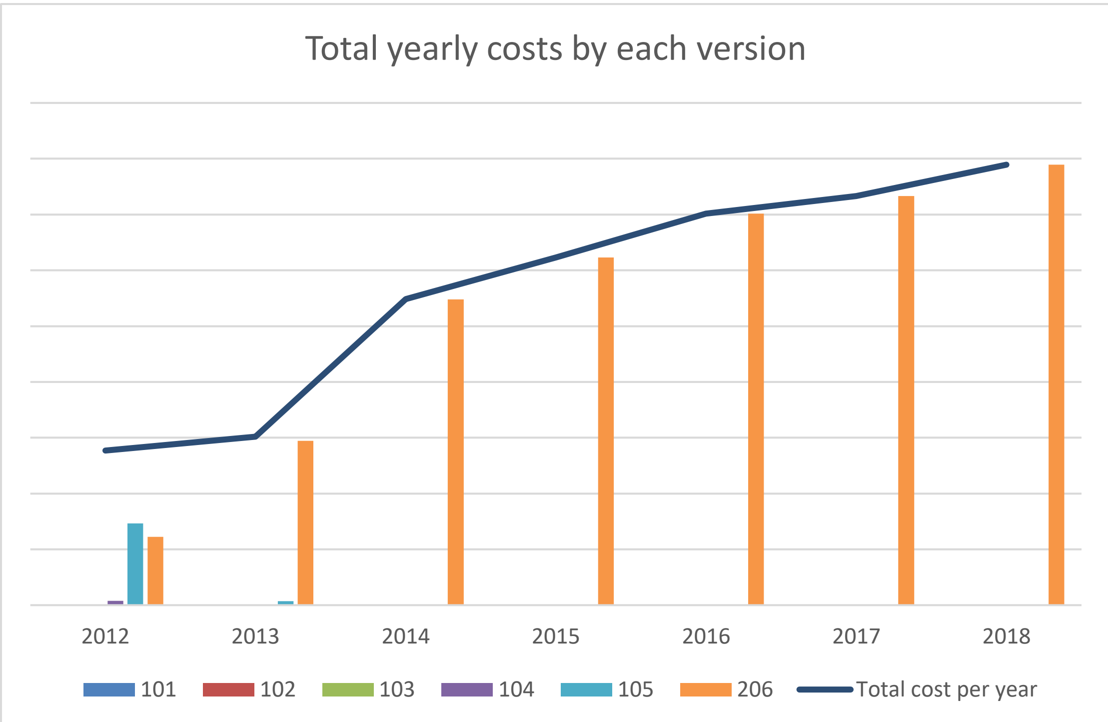


Chart 6. Total yearly costs divided to each version

4.2 Demo on how to utilize TO in cost reduction/quality improvement projects in product maintenance

According to the data I found, responsibility for PRODUCT X was shifted to PM after the release of version 102. This means that changes after that were made as cost reduction projects or quality improvement projects.

I performed topology optimization for PRODUCT X and created a design using the results. Next, I will go through the process of doing design using topology optimization combined with process flow I created. Below is a process flow chart combined with the stage-gate approach that I created for development projects of this kind.

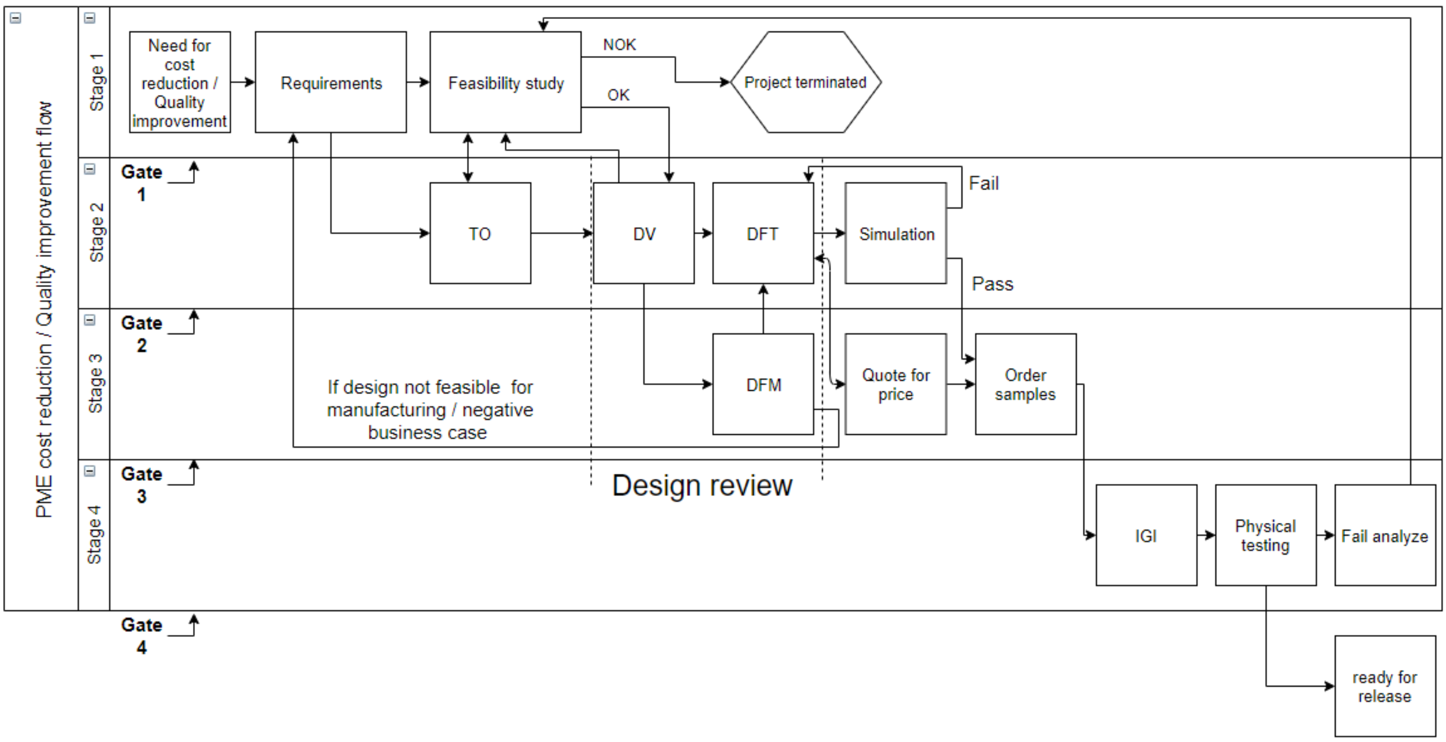


Figure 17. Cost reduction/quality improvement flow

As always, the project starts with a need for something, in this case the need to reduce costs. To start the project, product requirements must be clear; in the case of an already existing product all the required information should be available. Product requirements should include information about usable space, interfaces, fixing points, all the functionalities the product could or should have, all the loading cases it needs to withstand, target weight, production style and an initial price target. In addition, there could also be information on safety and usability requirements.

After requirements are clear and documented properly, the next step is to do a feasibility study. The point of a feasibility study is to go through the requirements and see if they are possible to execute within the target price. Topology optimization can be used to help with the feasibility study, since the first optimization will give some idea if the weight reduction is feasible. Another point of the feasibility study is to calculate an initial business case. If the business case is negative or not good enough the project could be shut down before spending any more resources on it. After the feasibility study is completed there should be a document available that describes the initial business case and a concept idea on how to implement required functionalities.

Next steps are topology optimization (TO) and design validation (DV). Both steps include many steps in themselves; below is a process chart for the actual topology optimization and design validation process, for clarity.

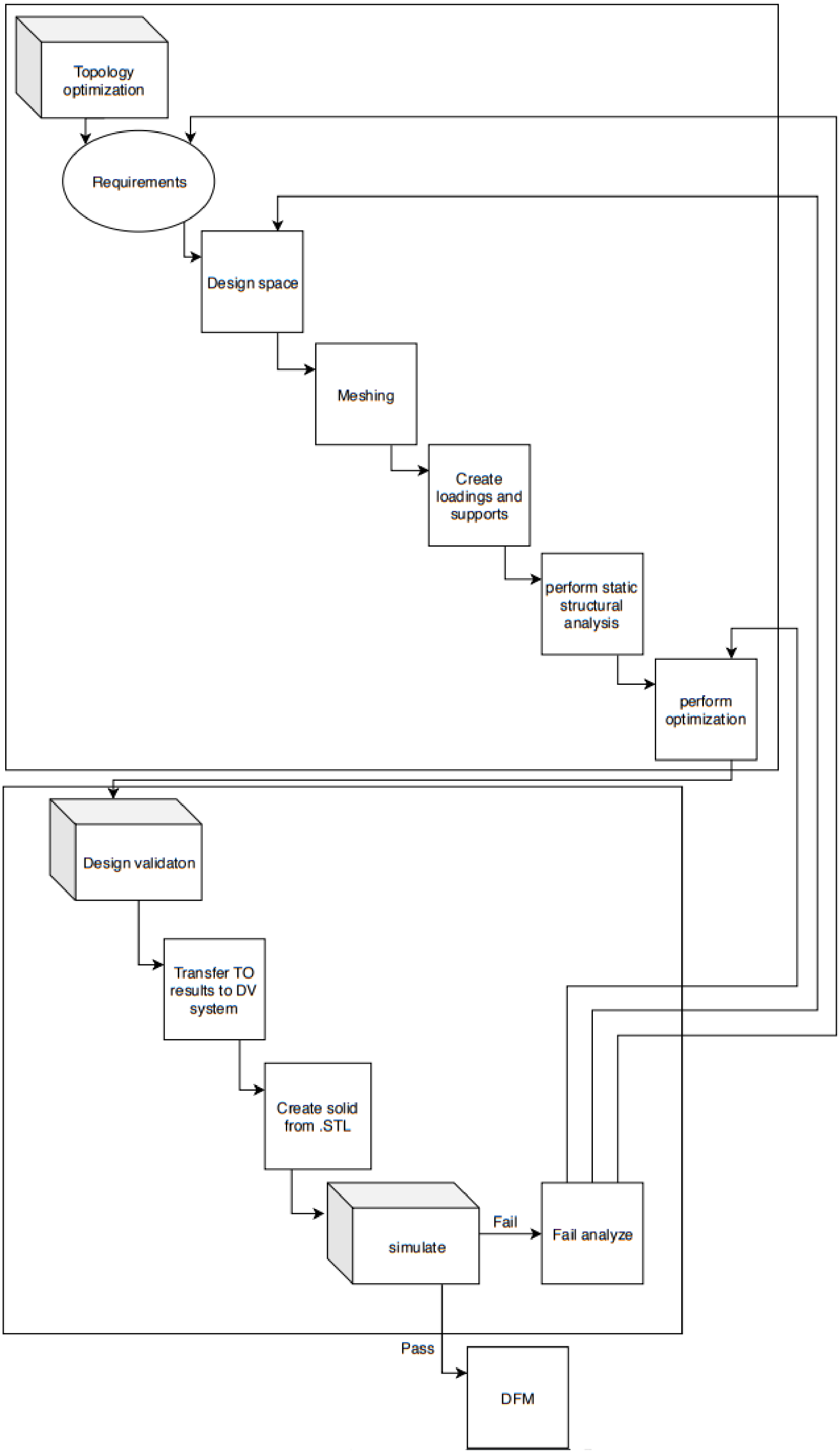


Figure 18. Topology optimization and design validation process chart

4.2.1 Topology optimization process including design validation

As stated earlier in this thesis I will be using Ansys' software for creating geometry, optimizing and simulating. To be more precise, all geometry is created with Spaceclaim and optimization, and simulation has been done with Ansys mechanical.

As seen in the above chart, topology optimization starts with defining requirements. In the case of optimizing an existing design, for example PRODUCT X requirements are clear from the start. Requirements need to include information about forces acting on the product, interfaces and possible features or geometries that need to stay in some exact position, as well as the production method and material.

After defining these requirements, the next step is to create a design space. It is the maximum volume available for the optimized geometry. This practically means that no geometry will be created outside the design space. When creating a design space, it is important to try avoiding abrupt angles. This is due to the fact that often the most efficient geometry for tackling moment is to create as much leverage as possible. That leads the geometry to form to the very edges of available design space. Of course, sometimes it is impossible to avoid making abrupt edges to the design space, as in this case.

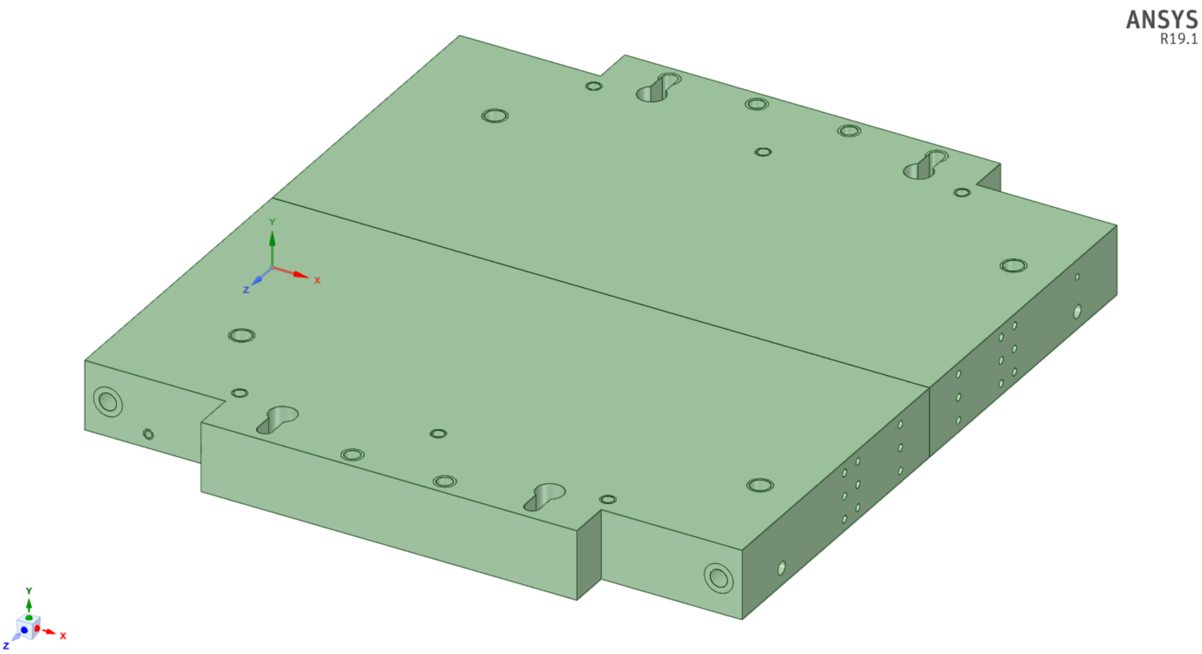


Figure 19. Design space for PRODUCT X optimization.

When creating design space, it is possible to cut it in half if the design is to be symmetrical or if it is known that both sides of the product will face same loading. Because of that, I cut an PRODUCT X design space down the middle. Doing this will reduce simulation and optimization times but it doesn't affect the accuracy of the result.

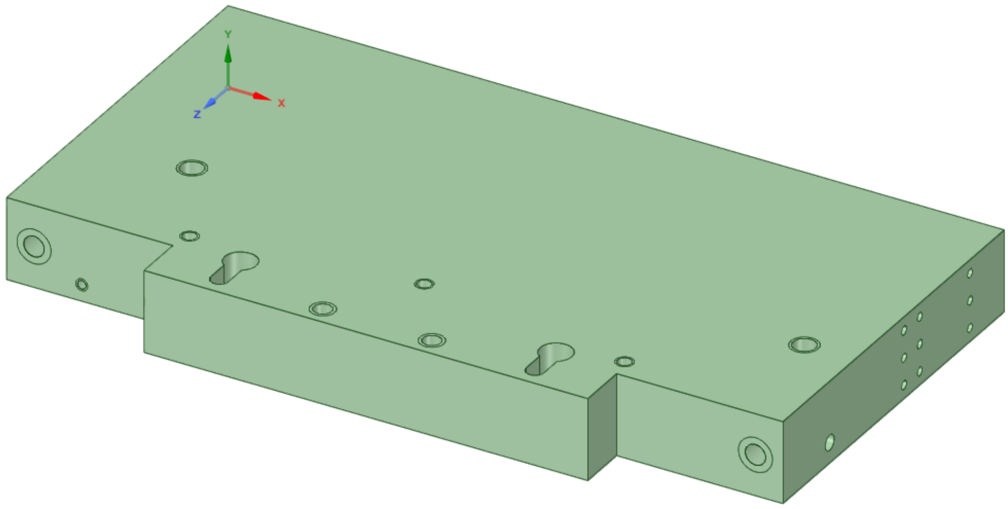


Figure 20. Design space cut in half.

The next step after creating a design space with Spaceclaim is to open the model with Ansys mechanical and create a mesh. Meshing is a very defining point in the topology optimization process. When creating a mesh, it is important to make it dense enough, so it captures every detail of the model and for ensuring that the optimizing result is accurate. When meshing, there is a tradeoff between accuracy and time. A denser mesh equals more accurate results but much longer simulation and optimization times, whereas a sparse mesh can give results faster but might not be accurate enough. Therefore it is important to find a balance between the two.

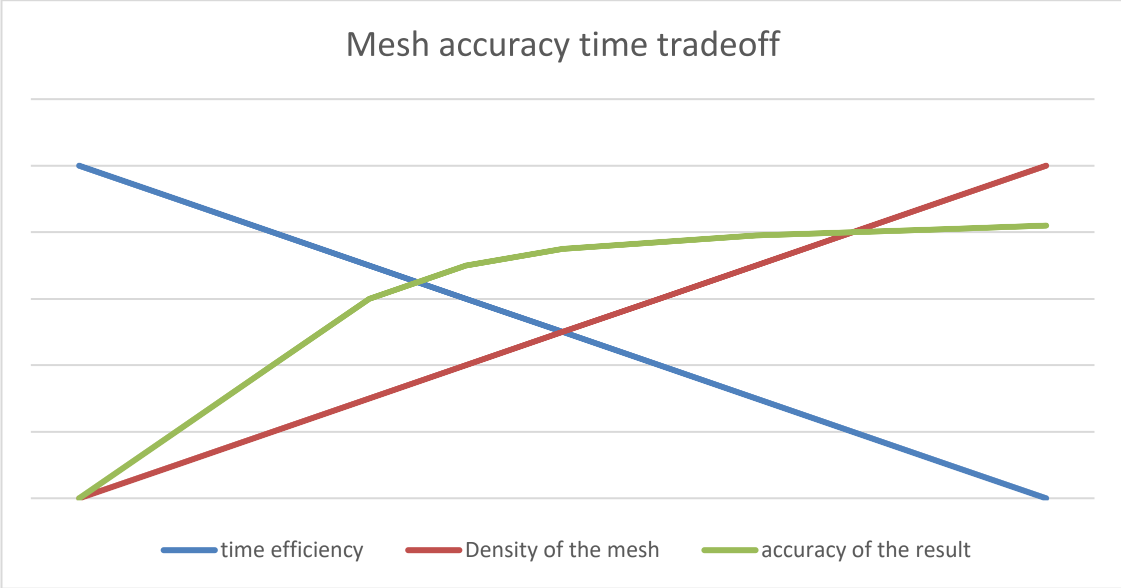


Chart 7. Mesh density’s effect on time efficiency and quality of results

At this point, the computer used in the project will have a tremendous effect on time efficiency. Having access to a fast computer with enough RAM and hard drive/SSD space is critical.

The computer used here has the following setup:

- Double Intel Xeon X5680 3.33GHZ (release date Q1 2010)
- RAM 96.0 GB
- Nvidia Quadro FX 3800 (release date Q1 2009)
- 931 GB hard drive

All the times for simulation and optimization mentioned are for the setup above. Below is the mesh I created for the optimization of PRODUCT X.

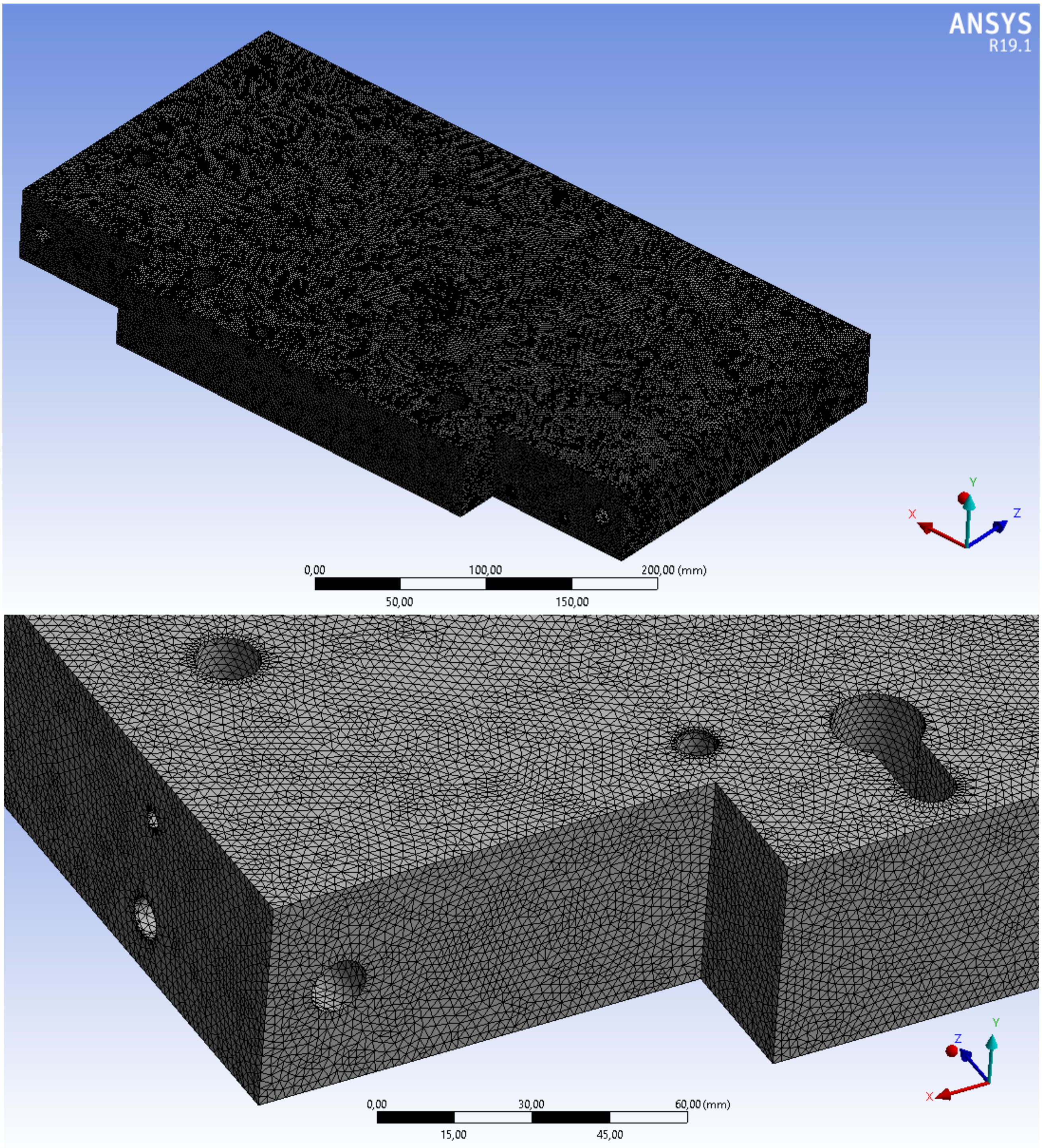


Figure 21. Mesh density example

Above mesh is fairly dense, especially around the holes. When creating a mesh, it is possible to control it so that certain areas are denser than others. This may be helpful when optimizing large products. In this case I have constrained the size of the mesh to be 2mm with the Face sizing tool.

Scope	
Scoping Method	Geometry Selection
Geometry	80 Faces
Definition	
Suppressed	No
Type	Element Size
Element Size	2, mm

Figure 22. Mesh control tool

After the designer is happy with the mesh density and quality, it is time to move on to creating loading cases. When simulating stresses, it is almost always necessary to create multiple static analyses. This is due to the fact that if one force acts on direction X+ and another on X-, they will cancel each other to some degree. Before this step, calculations have been made to know the acting forces. Another possibility is to create a space model that matches the maximum load case in both weight and space and then give the forces as acceleration. For a simulation designer must define where the forces/accelerations act and to what direction, as well as where the product is supported and in what way. Supports can be modeled to have freedom in some directions. Below are all the static structural analyses needed for PRODUCT X optimization. These cases include every loading case for PRODUCT X.

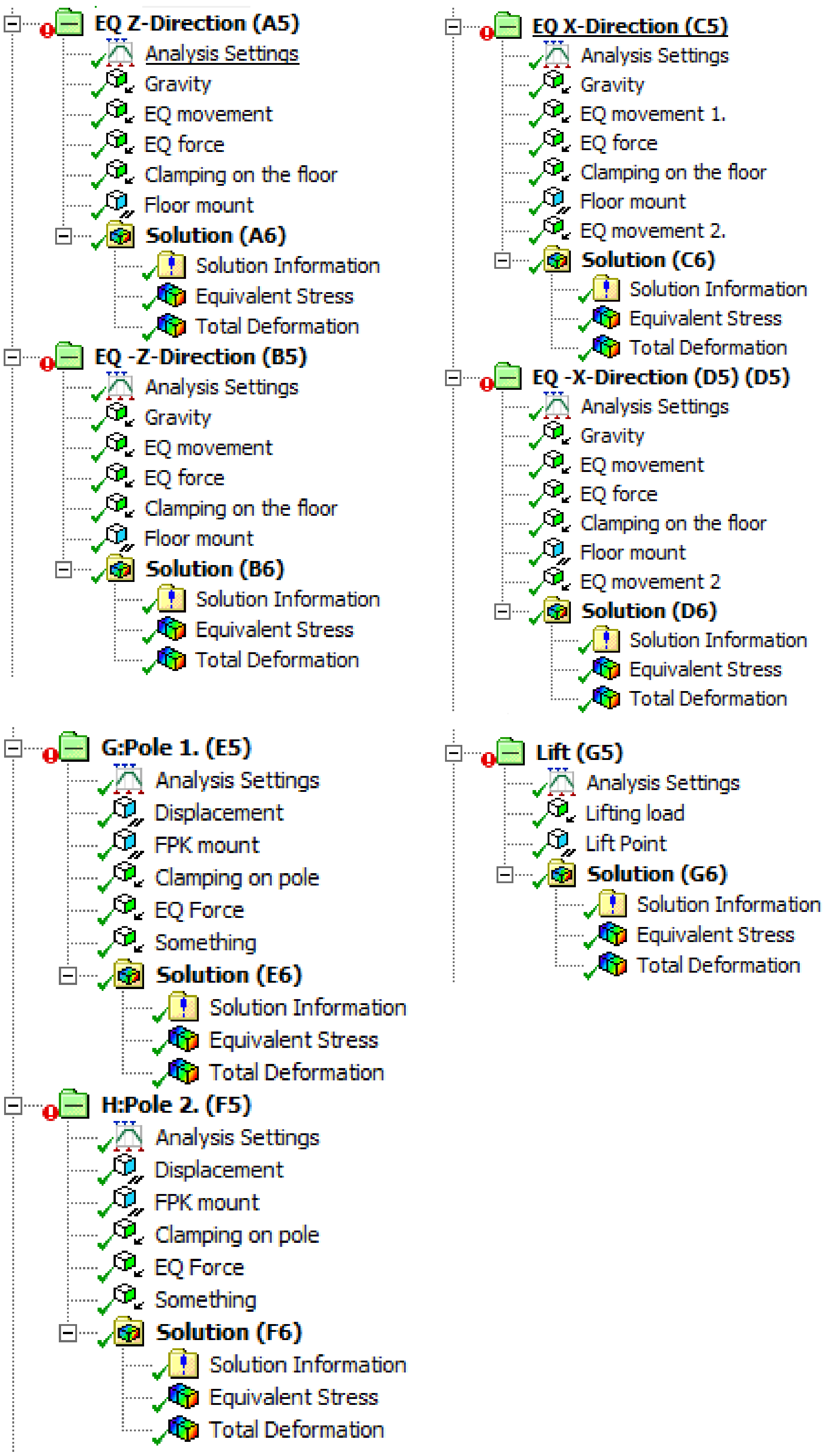


Figure 23. Loading cases for PRODUCT X static structural analysis.

As can be seen in the above pictures, each case is for a specific direction and each case contains multiple loadings. Below is a closer look at one static structural case. In the pictures below red arrows express different forces, where they are directed and the direction they affect. Letter E shows where the supports are in this particular case.

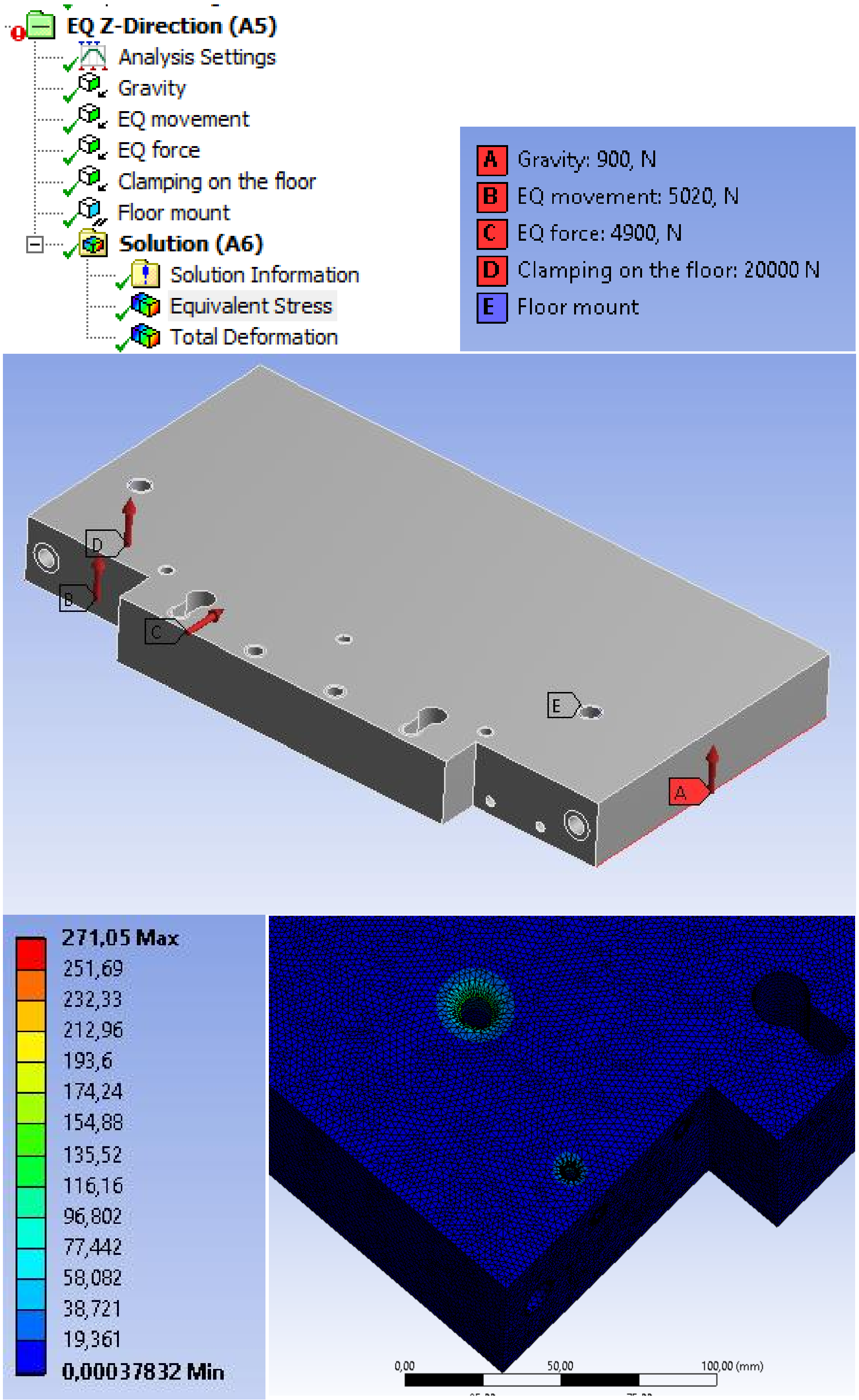


Figure 24. Closer look at a static structural analysis

The bottom right picture shows the resulted stresses from the forces. The whole geometry looks blue which means that there are practically no stresses whatsoever. This of course insinuates that much of the material can be removed before reaching critical stress levels.

After performing a static structural analysis, it is now possible to move on to topology optimization. Static structural results can be imported to the TO system which then uses them to find the optimized shape. Below is the way it looks like in the Ansys workbench interface.

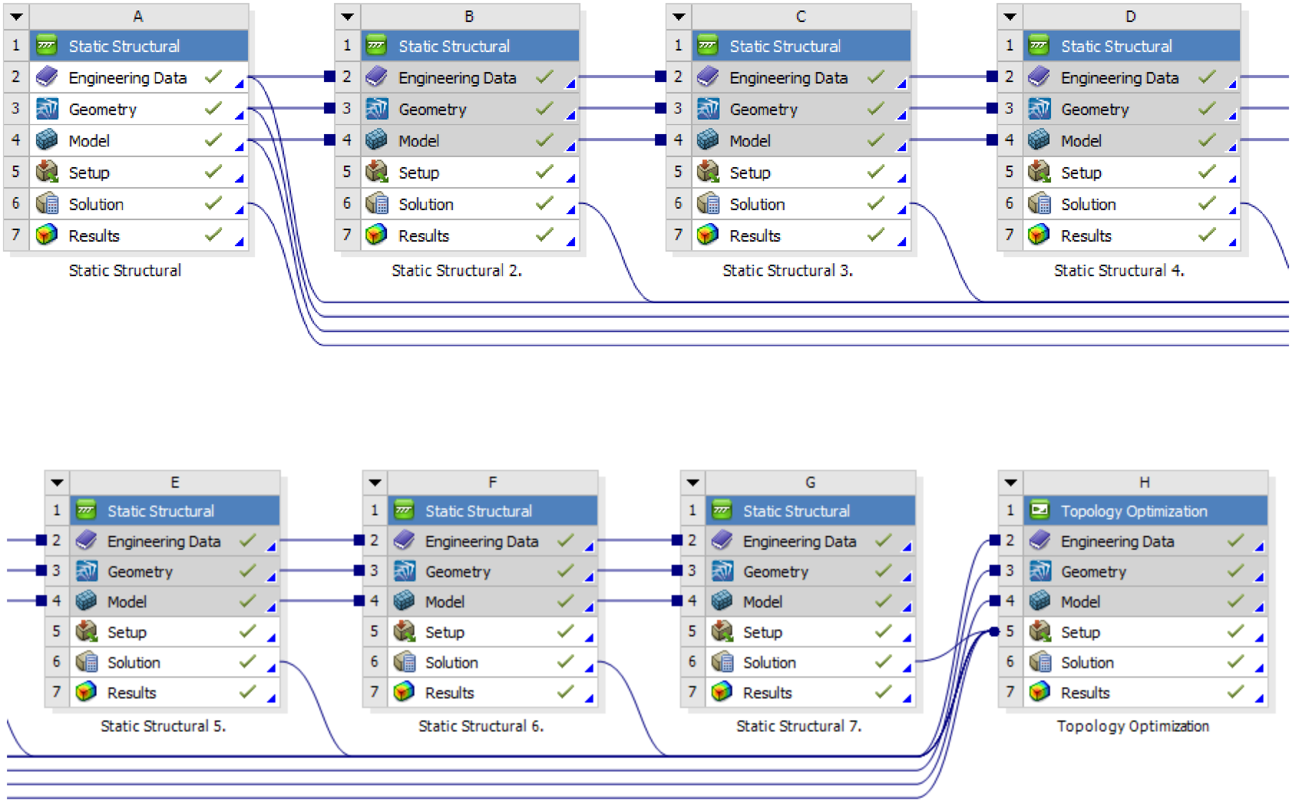


Figure 25. Ansys workbench

Now, when performing topology optimization, constraints and objectives must be defined. Normally, the objective is to optimize for minimum compliance. The reasons for this are found in the theory section of this thesis. For this optimization I used ”pull out direction” manufacturing constraint, as PRODUCT X is a die-casted part. It is necessary to define retained mass and for this project I optimized for two different values, 7% and 15%. The next step is to define exclusion regions from the design space. Normally these are interface areas that need to remain exactly the same. The software then leaves these areas untouched.

Enabled	Response Type	Goal	Formulation	Environment Name
☑	Compliance	Minimize	Program Controlled	EQ Z-Direction
☑	Compliance	Minimize	Program Controlled	EQ -Z-Direction
☑	Compliance	Minimize	Program Controlled	EQ X-Direction
☑	Compliance	Minimize	Program Controlled	EQ -X-Direction (D5)
☑	Compliance	Minimize	Program Controlled	G:Pole 1.
☑	Compliance	Minimize	Program Controlled	H:Pole 2.
☑	Compliance	Minimize	Program Controlled	Lift

Table 2. Objectives of optimization and used loading cases

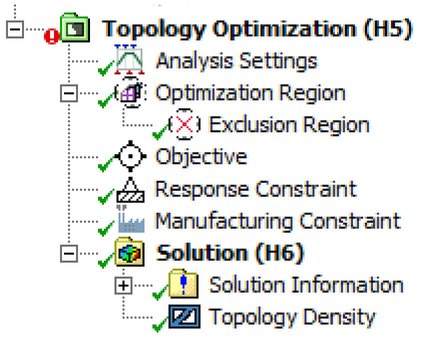


Figure 26. Topology optimization

After defining and performing all these steps it is possible to start the optimization. My PC setup, with the described mesh density, calculated the optimized topology in 58 hours. That is a fairly long time, but while the computer is calculating the result, the designer can do something else, as the optimization process doesn’t require active participation.

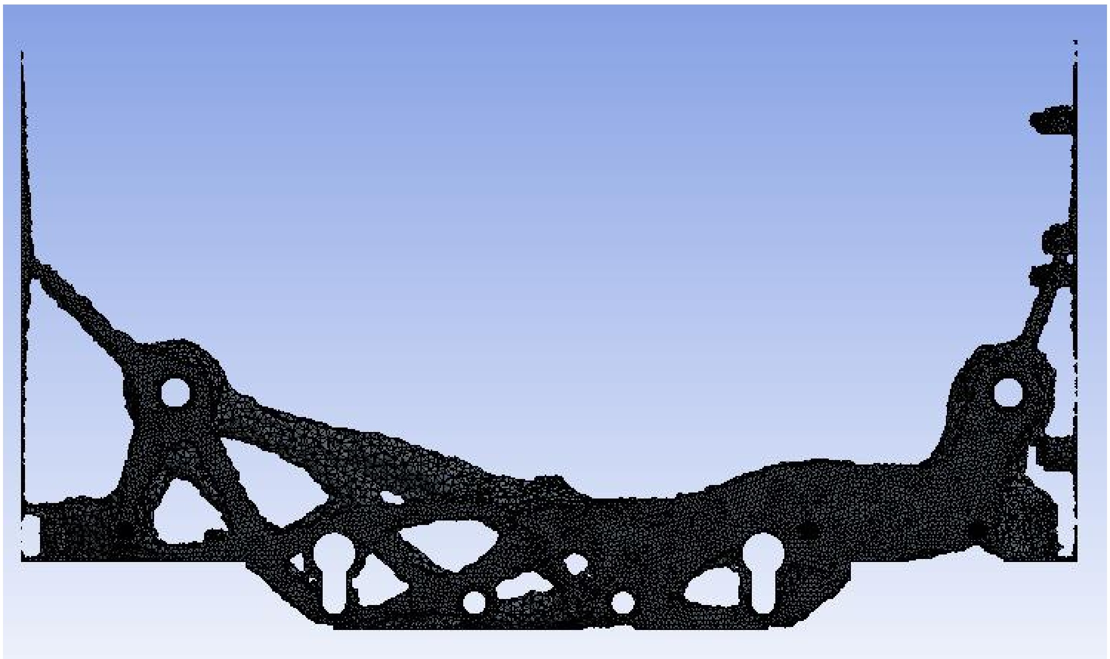


Figure 27. Result of topology optimization, retained mass 15%

Figure 28. Result of topology optimization, retained mass 7%

The result of topology optimization is an STL file. With the solver I used in this optimization, the result is often very rugged and not feasible for manufacturing as can be seen from the picture below.

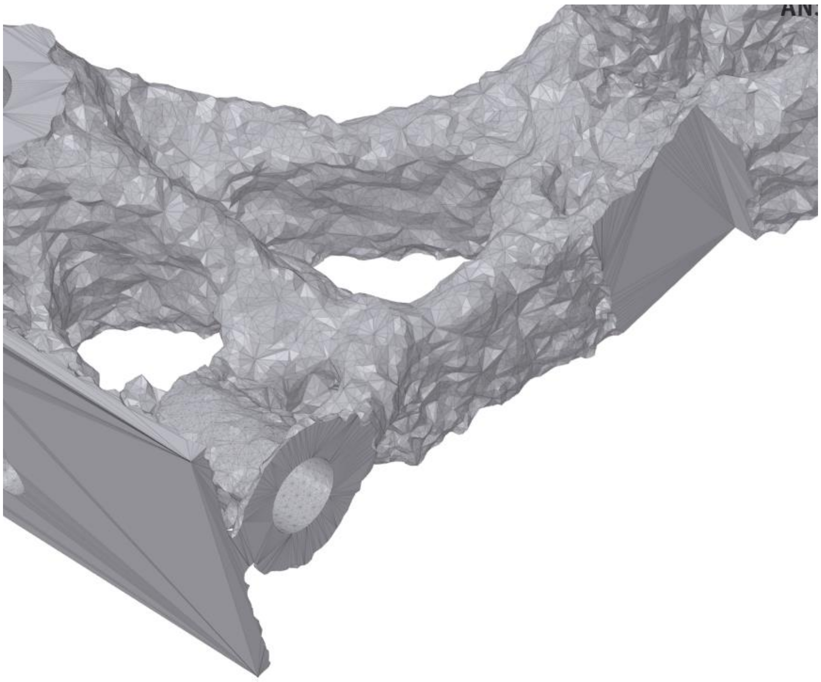


Figure 29. Closer look at the result.

Therefore, the next step is to smoothen the result with Spaceclaim. This smoothening is part of the design validation step, whose purpose is to create a solid part from the STL surface part so that it then can be simulated again. After that simulating, it is possible to say if the design is strong enough and if it is worth it to start fine tuning it.

First thing to do in DV is to create the solid part. I start the process by first smoothening the STL file with spaceclaim's automatic tools such as shrinkwrap. Other tools available include smoothening, regularize and sharp edges removal. Below is a picture that shows how the part looks like after the smoothening operations. There is no one right way of doing these steps, as different things work best for different geometries and other designers may prefer a slightly different look. Still, the basic idea is to get rid of all parts that are not connected to anything and to make the surfaces as smooth as possible.

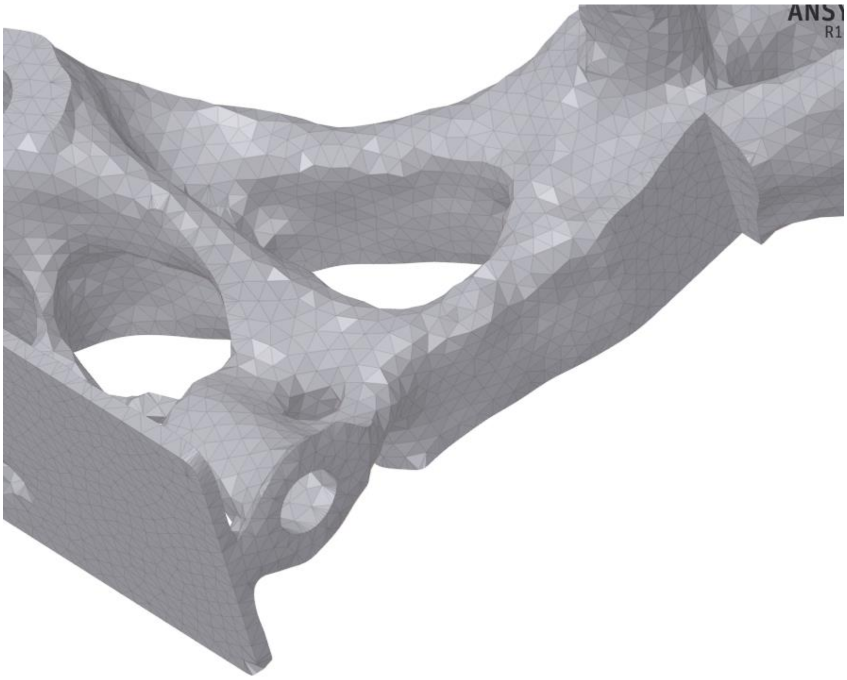


Figure 30. Smoothened topology optimization result

After the smoothening process, the next step is to create the solid part. After some testing and research I have concluded that there are three different ways of doing it. Each method has their benefits and flaws. The three methods are:

1. Convert straight to solid
2. Use the skin surface tool
3. Use design space as a basis and cut material off using the TO result as a guide

In the first method, converting straight to solid, the software creates a face for every facet if they do not happen to be aligned to one plane. But usually this means that the solid part will have thousands of faces. This will lead to the fact that the model is practically impossible to export since it will be such a large file. Also, simulating this kind of solid is a slow process. In short:

+ Fast for getting solid

+ Works quite well for small uncomplex parts

- Makes the model heavy and almost always impossible to export

- Makes simulating of the design slow

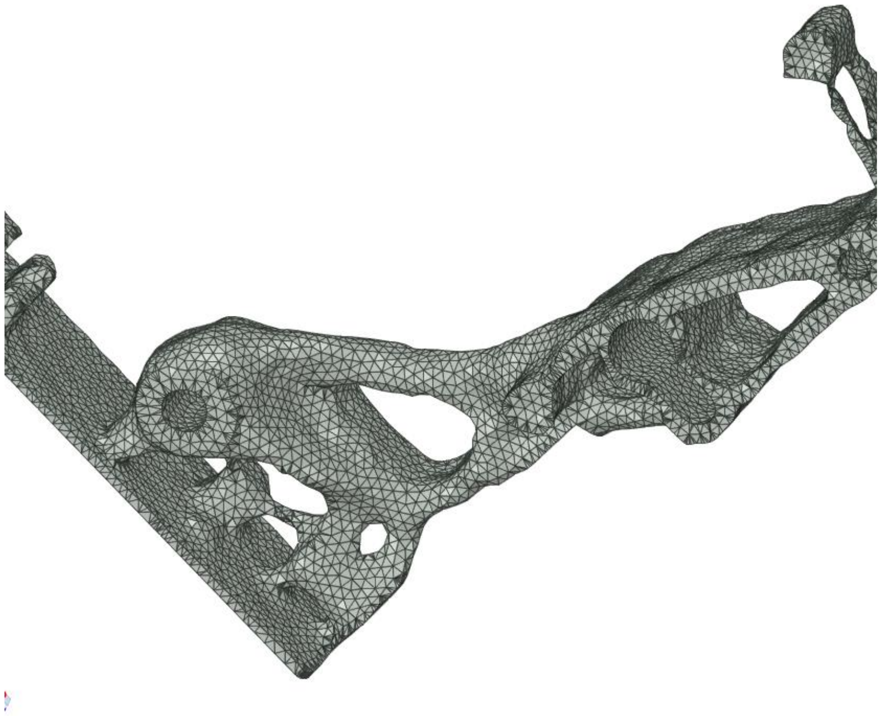


Figure 31. STL converted straight to solid after initial smoothing

With the second method, using the skin surface tool, it is possible to almost exactly copy the shape of the topology optimization result. With the skin surface tool it is possible to have considerably less faces compared to converting STL straight to solid. This also means that the model is easier to handle during simulation and other possible actions, such as exporting. Using the skin surface tool can be slow and quite frustrating at times, but it can be done. As a comparison, when converting straight to solid it takes around 1 to 15 minutes, but with the skin surface tool it could take anything from 15 minutes to 8 hours depending on the part. For PRODUCT X this process took around 8 hours with my setup. So, in short:

+ Accurate representation of TO result

+ Easy to perform simulation

- Can take a long time to make

- Usually not manufacturable shape, only to be used for design validation/concept proofing

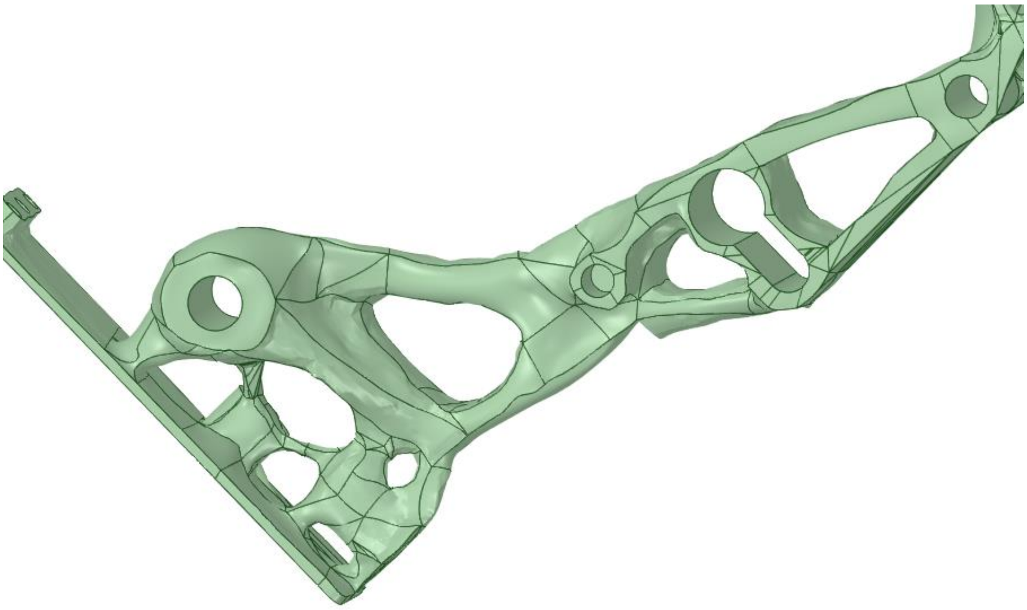


Figure 32. PRODUCT X converted to solid using the skin surface tool

The last of the three methods is using the design space as a basis and cutting extra material off it by using the TO result as a template. This method is quite straightforward and simple. The simpler the shape the easier the process, but not even complex shapes should cause any trouble, just lengthen the time to make the solid. The downside is that the solid will be a bit different than the TO result. Smallest data size, easiest to handle and simulate. In short:

+ Quite fast

+ Easy to perform simulation

+ Manufacturable shape

- Not as close to TO as the two others

Basically, a designer can use any of these methods, but in my opinion best choice depends on the size and complexity of the product as well as production method. My recommendation is to use the last method described, forming solid straight from the design space. I recommend this option because it enables fast design validation, and no matter what the product looks like in this point, design fine-tuning must still be done.

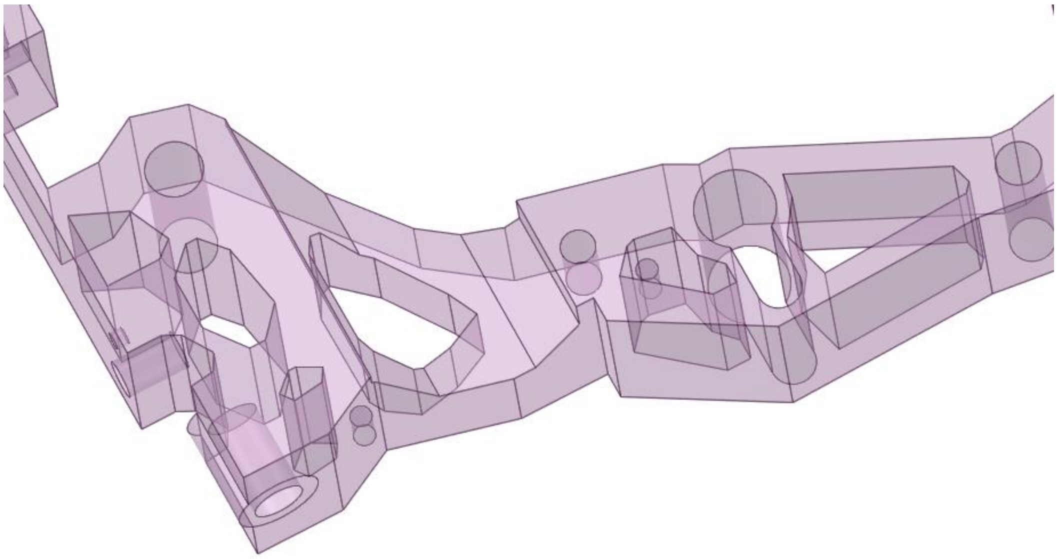


Figure 33. PRODUCT X solid created from design space

There are some exceptions, as the STL file is a valid file format for most 3D printers. This basically means that if the part is made of plastic or some other cheap material, if it is quite small, and if there is an in-house printer, the product could be printed right after the smoothing phase. But when talking about larger products that are, for example, made from aluminium, such as PRODUCT X, this kind of rapid prototyping is not feasible. PRODUCT X could be printed with some AM machines but the time and cost would be too great and therefore it is much more feasible to finalize the design and simulate it properly before moving on to physical testing, as stated in the process chart (Chart X.) shown earlier.

No matter which way the transformation from STL to solid is done, it is crucially important to check that the geometry does not have errors in it before continuing. These errors may prohibit mesh formation or cause other issues when simulating, and Ansys mechanical does not know how to tell you that it is because of problematic geometry.

The next step after creating the solid part is to simulate it. By this, it is possible to check if the design is strong and rigid enough. The work bench has a neat feature that allows you to click on the topology optimization cell to create a design validation system. This will copy all the static structural analyses used for the optimization. Simulating in the design validation phase works the same way as before, so everything starts from meshing and after that defining the forces and supports. Although analyses are copied to the design validation system, the designer must redefine everything. This should not take long if the solid part is created well enough. After defining everything and running the initial static structural analyses, it is possible to see if the design created is good enough to continue simulations further, whereas if simulations show that the structure undergoes too much stress, it is necessary to do a fail analysis and after that decide the next action. That could be, for example, going back to TO and changing the retained weight value.

Required simulations differ depending on the product, or, rather, where the product is used. In this thesis, the scope includes mechanical parts. At Telecommunications firm, mechanical parts are almost always used in outside environments, and quite often the parts are exposed to rain, wind, vibrations, earthquakes etc. So, at the moment, required simulations for mechanical parts include wind load, modal, earthquake, shock and random vibrations. For a person who is familiar with these simulations, the actual simulation process should not take more than 16 hours (2 workdays). Since simulation of the things mentioned above is quite a long process, I will go through it in its own chapter.

As in all design/new product development, cost reduction and quality improvement projects, it is paramount to have design review meetings after each phase, as this enables other members of the team to comment on the design as soon as possible. This makes it so that new requirements or changes to old requirements surface as fast as possible, as no one wants to do work for nothing and then start over because of new requirements.

When developing cost reduction or quality improvements for a product, its manufacturability is one of key factors for a successful project. That is why my process flow includes DFM, which stands for Design For Manufacturing. First DFM discussions can start after the DV phase is ready and the designer has a draft version of the product. This makes it possible to ask for first quotes from the manufacturers and therefore also possible to check if the business case is still at a feasible level. Also, if manufacturers have remarks on the design to lower its price or to make it more manufacturable, which often leads to lower price, those remarks are easy to implement at this stage.

After initial DFM discussions and after implementing possible changes, it is time to start design fine tuning (DFT). At this point the design gets the last changes, for example if the product is casted, as PRODUCT X is, releases need to be added in this point at the latest. Then holes and possible threads need to be added, but when doing CR/QI all information such as what thread to use is known, so this phase should not take more than a week, of course depending on product.

After design fine tuning is ready and the product is practically ready, it still needs to be simulated just in case. Simulating is easy since the simulation environment is the same that was created earlier. Parallel to simulation the final quote for the product should be asked from manufacturers. If the business case is still good enough and the design passes simulation, samples can now be ordered.

4.2.2 Physical testing

Telecommunications firm has a protocol where all incoming goods go through the inspection of incoming goods (IGI) process. In short, the idea is to check if the product meets the required quality standards. If IGI is not a "pass", then the supplier must be contacted, and a discussion started on what is wrong. Often possible problems are a bad surface finish or unreadable casting clock/markings. If IGI is passed, then products will move on to physical testing.

Telecommunications firm has an onsite vibration table that can handle basic vibration tests, but the earthquake test is bought from a service provider. If the material is new or the product has new material pairs, then the materials must also be verified. The material verification process is a long process and if it is in any way possible, known materials and material pairs should be used to avoid this step altogether.

Tests that are relevant in the scope of this thesis are the following:

- Vibration
- Shock
- Earthquake
- Wind driven rain
- Usability

All above, excluding usability, can be simulated.

If the product fails any of the tests, fail analysis should be done to figure out why, as product breaking can be caused by poor manufacturing or incorrect testing, in addition of just breaking because the design was not enough strong.

When testing prototypes for to be casted parts, it's common that the prototype is fully machined instead of casted because die casting mold for aluminium can cost around 100 000 euros. Therefore, if the prototypes pass and the production is started, the casted plus machined version will also be tested.

In a mechanical design point of view the product is ready for full release after physical testing is concluded.

4.3 Potential cost savings if TO with the suggested process flow was used

In the previous chapters I have gone through how the PRODUCT X has been developed, and how it could have been developed with TO and the process flow I have created around the use of TO. Next, I will explain and go through the business benefit that could come from implementing the suggested process flow. I will also discuss the results of PRODUCT X demo case and how much the design I created using the suggested process flow differs from the current design.

Point of these calculations is to show how much cost savings can be cumulated from one product, which in this case is PRODUCT X. Some of the calculations such as how long the process took is information I have collected through my research and by doing all the design steps myself.

Two main cost drivers for aluminium parts are the cost of the mold and raw material. By topology optimization it is not unreasonable to expect a raw material reduction of up to 30%, compared to regular design (Krog et al. 2002).

Other costs in developing anything of course include the time it consumes from the people getting paid. Also, ordering and testing physical samples is a significant expense, especially if multiple rounds are needed to reach a wanted result.

As mentioned earlier, data about yearly costs and volumes is available only upwards from 2012, PRODUCT X was first released in 2006 and the latest version was released 2012. This means that the calculated saving is not as much as it would be if data would have been available from 2006.

4.3.1 Topology optimized version vs current version of PRODUCT X

As stated earlier PRODUCT X has been released 2006 and the current version weighs 2,65Kg, and was released 2012. I have two different versions of topology optimized geometry; one is made with skin surface tool and other is approximated from the TO result by cutting material from the original design space. The weight of the skin surface tool model is only 1,99Kg which is around 24,8% lighter than the current design. The approximated geometry weighs 2,67Kg which is actually 0,75% heavier than current design.

Design	weight (Kg)	Proportional weight
Current design (.206)	2,65	100 %
Skin surface tool design	1,99	75,20 %
Approximated from TO design	2,67	100,75 %

Table 3. Weights of different designs

It's not surprising that skin surface design is clearly the lightest since it follows the TO result almost perfectly. As it can be seen from the pictures´, there does not seem to be that much difference between the approximated design and the skin surface design even though the weight difference is over 25%. This goes to show that recreating TO results accurately is not always easy, it also shows how much weight can be saved by just having slightly less material overall. Figure 37. shows approximated design on top of skin surface design.

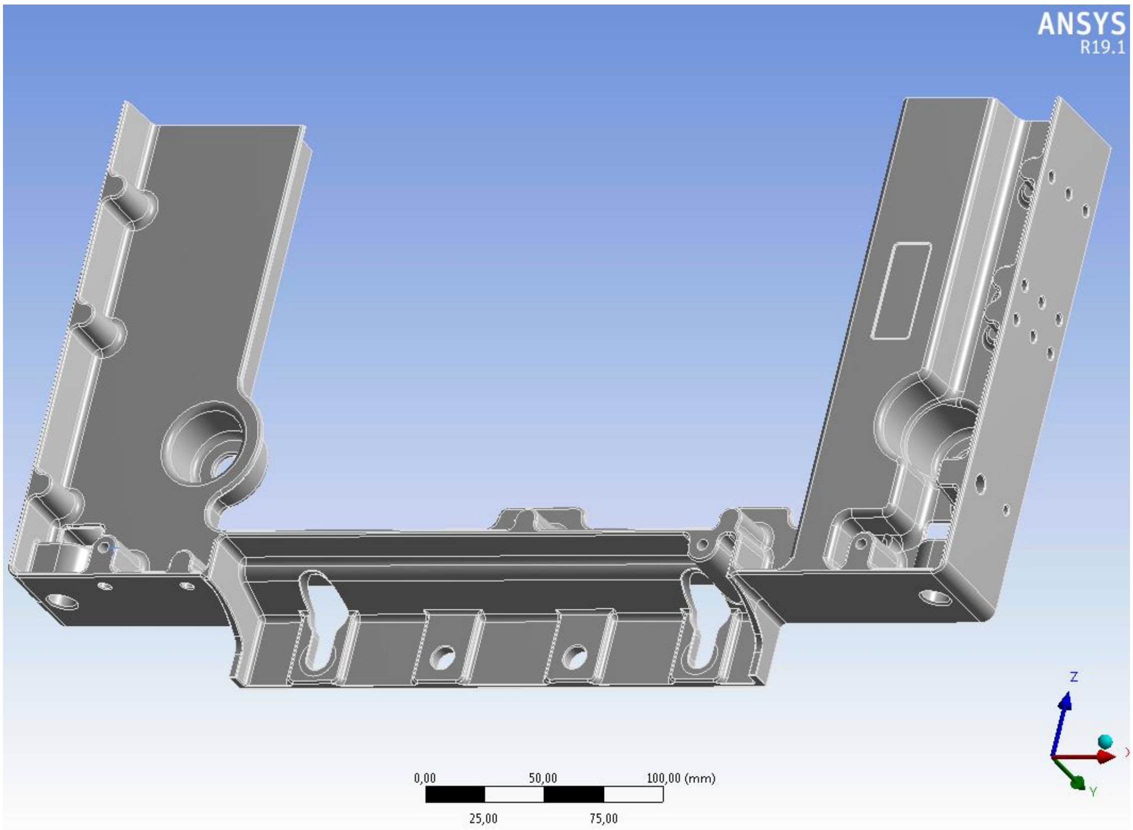


Figure 34. Current version of PRODUCT X (.206)

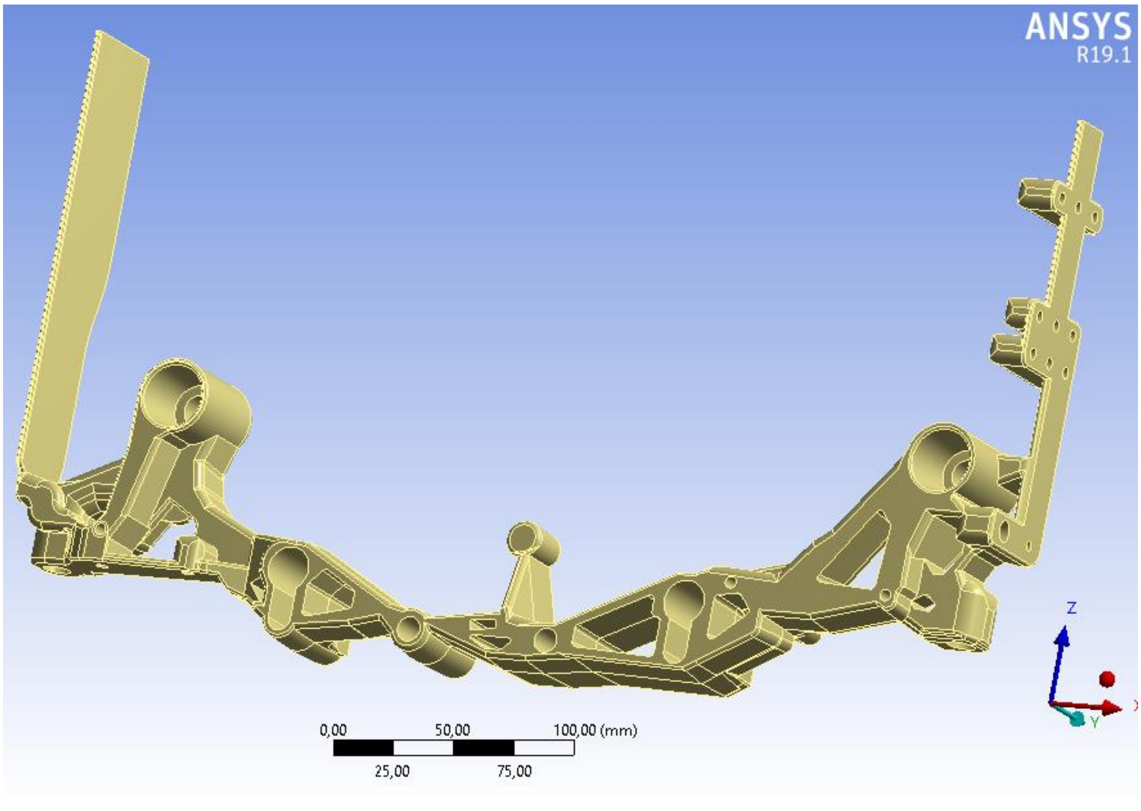


Figure 35. Approximated design

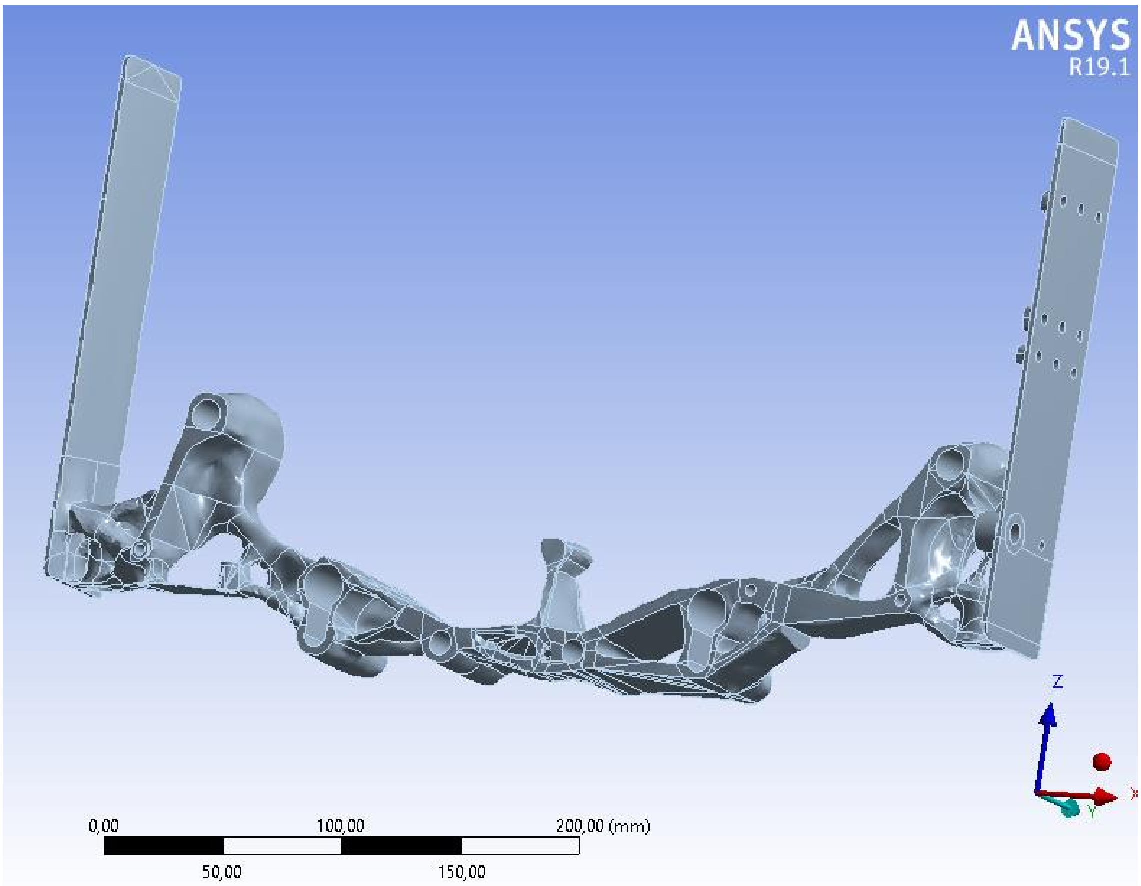


Figure 36. Skin surface design

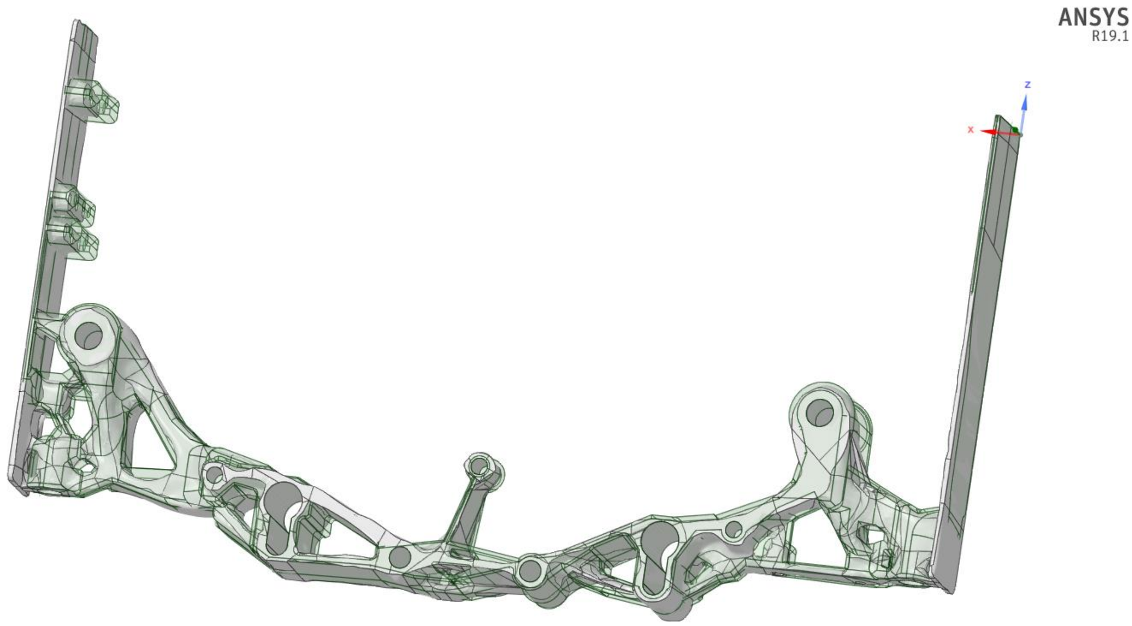
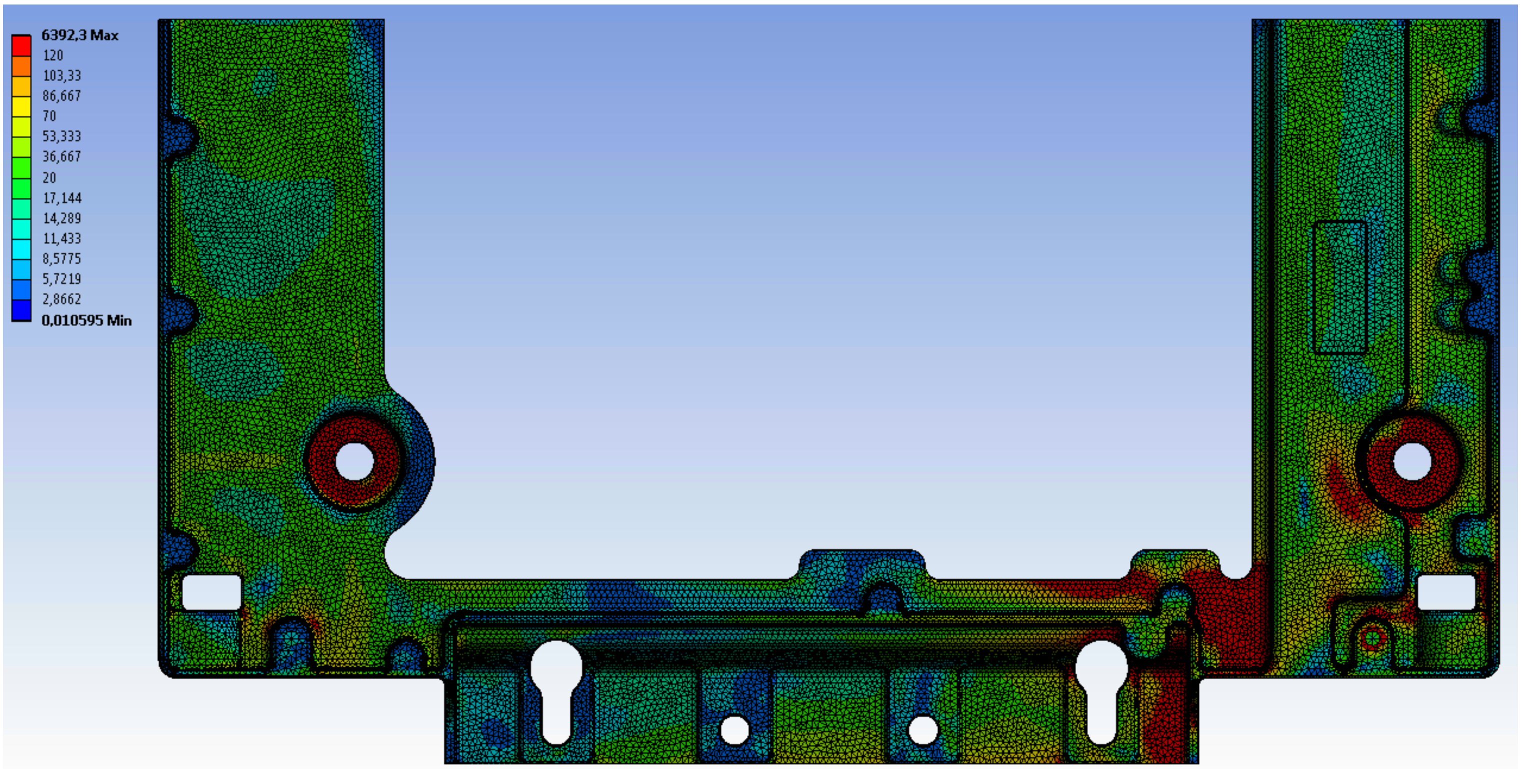
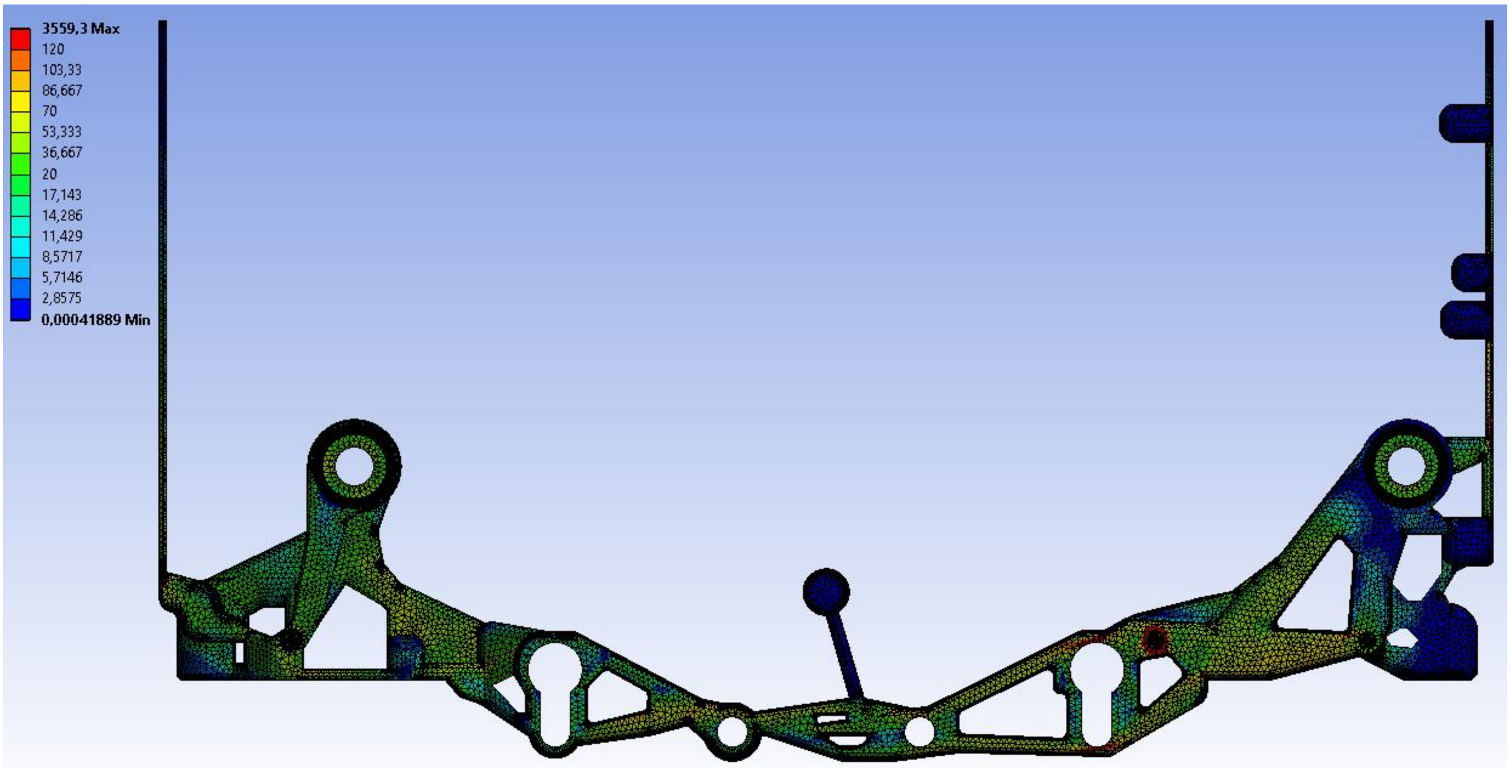


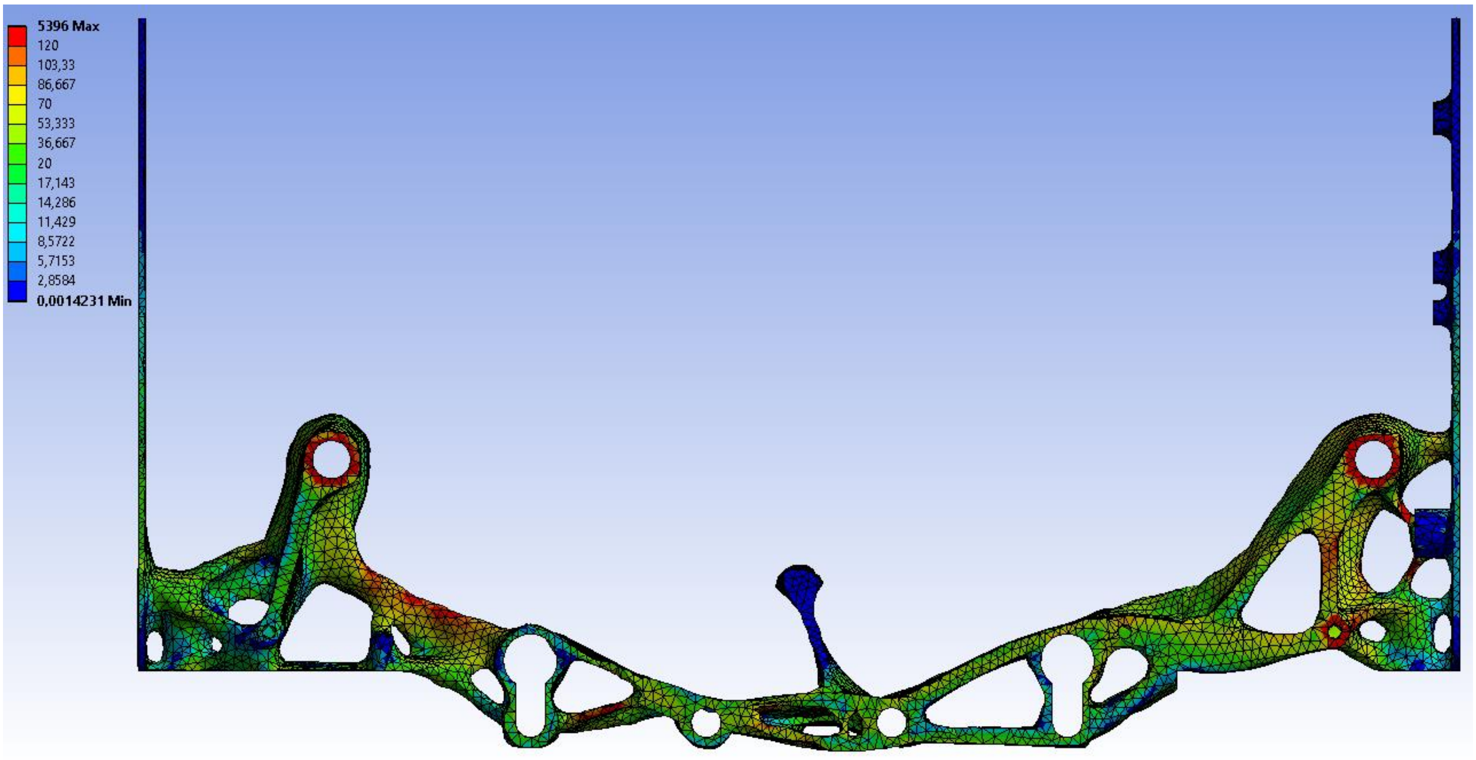
Figure 37. Approximated design on top of skin surface design.

I performed the same simulation analysis on all these different designs; these are same structural loading cases that were used for the topology optimization. There are seven different loading cases and here I will present the results of the four most stressing cases. Below are pictures of simulation results. The order is always current design, then approximated design, and last the skin surface design.

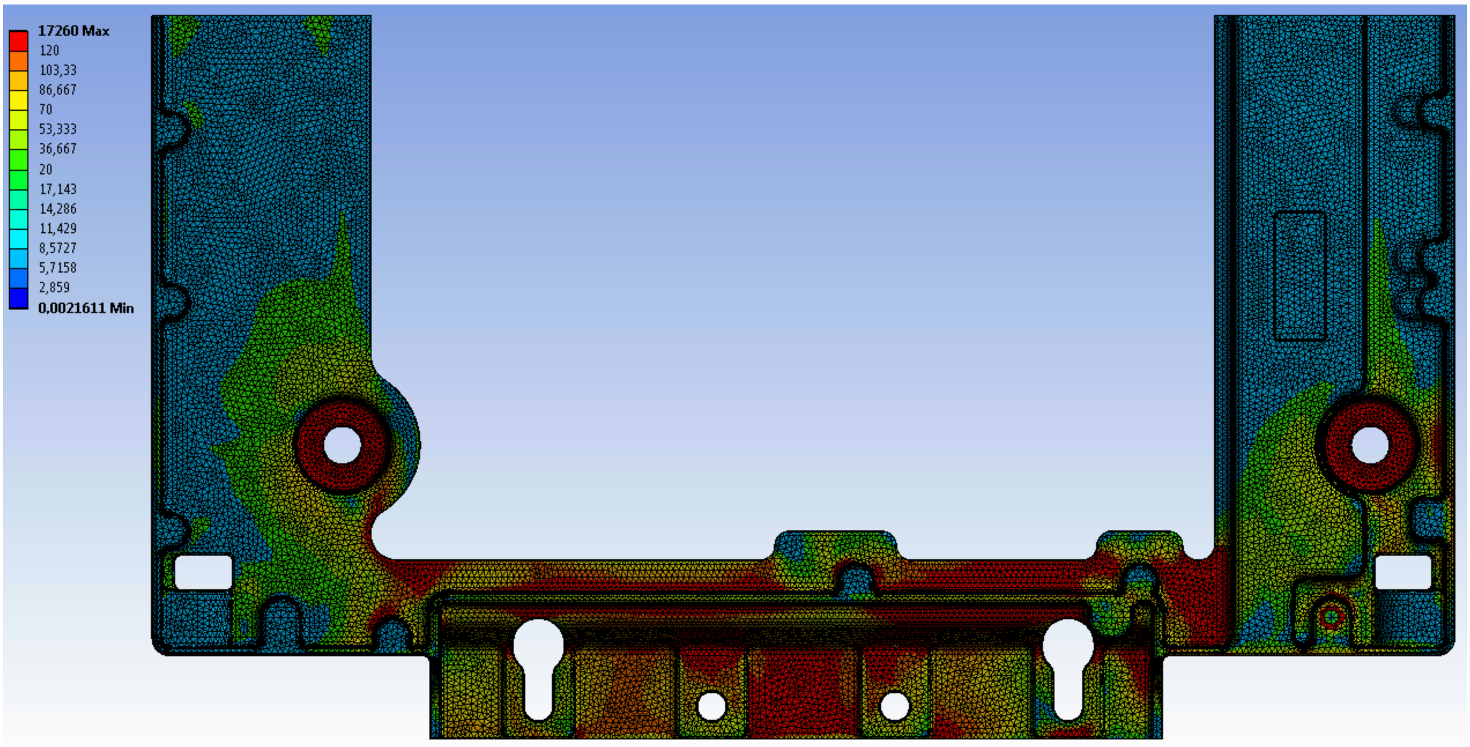
Simulation case: Earthquake Z-Direction

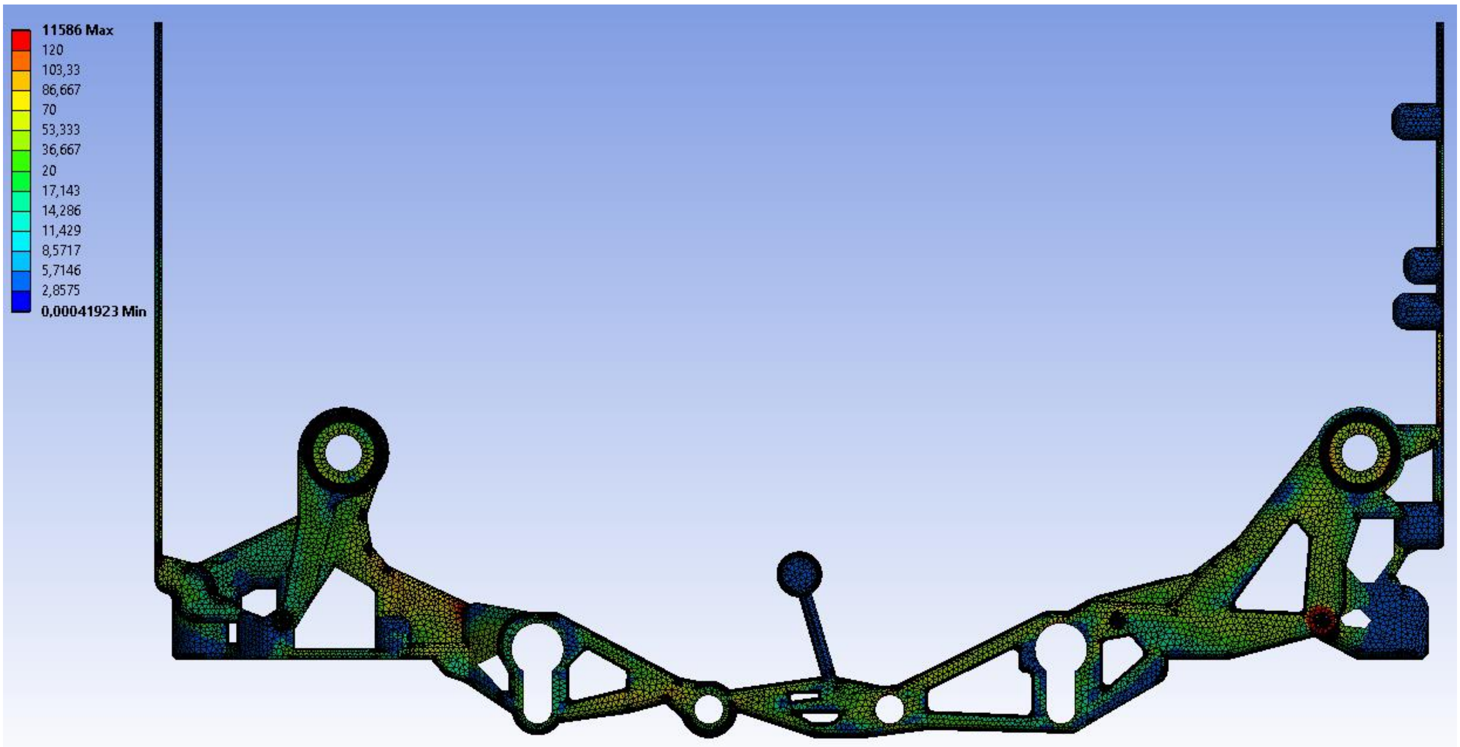


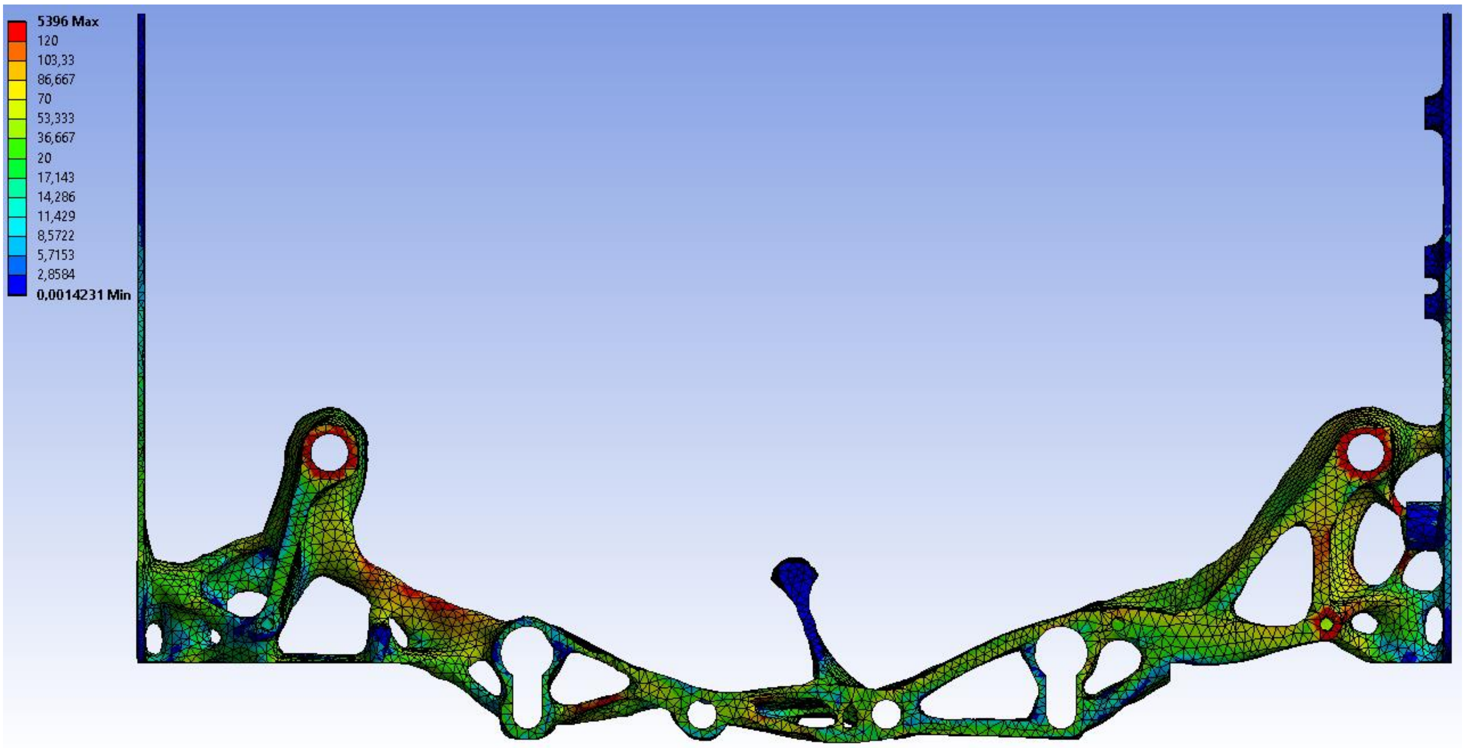




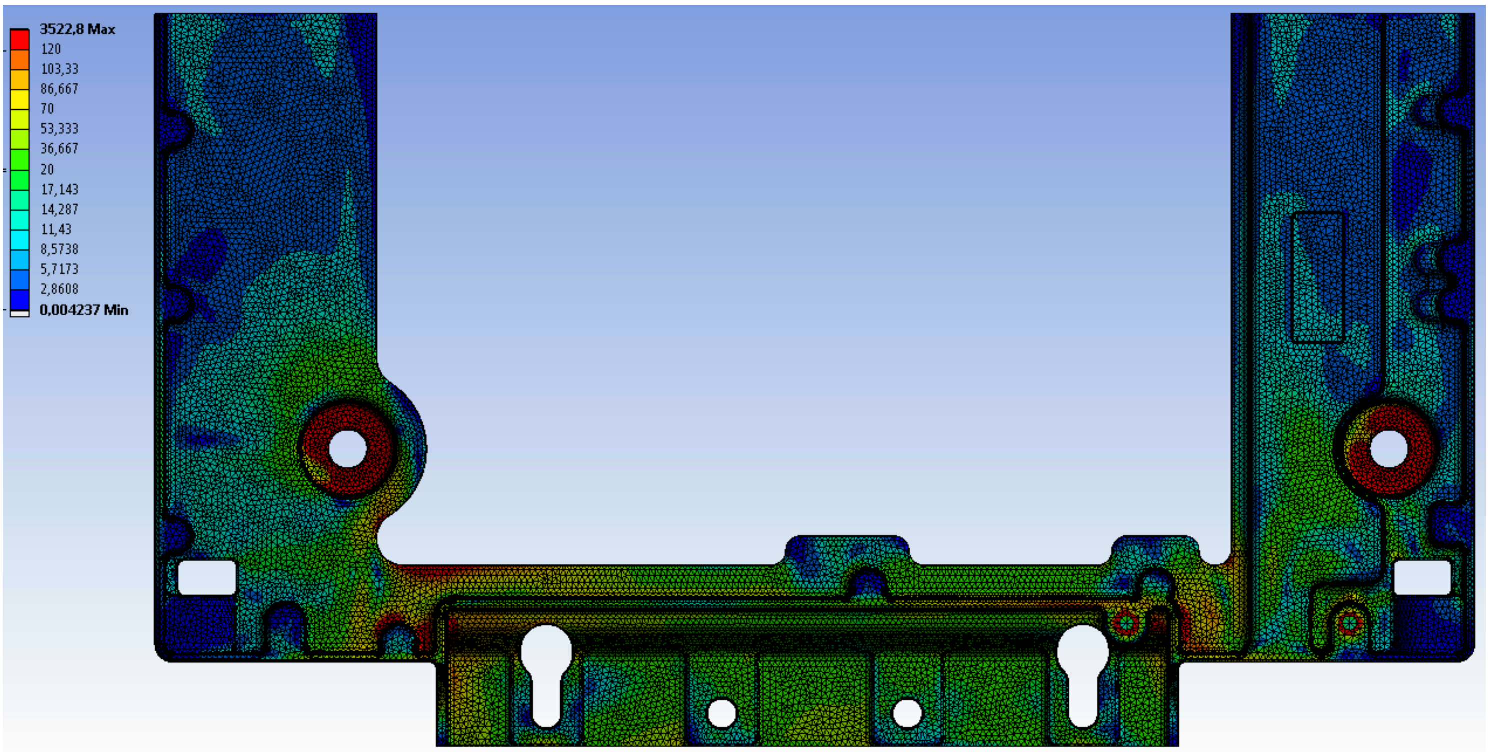
Simulation case: Earthquake -Z-direction

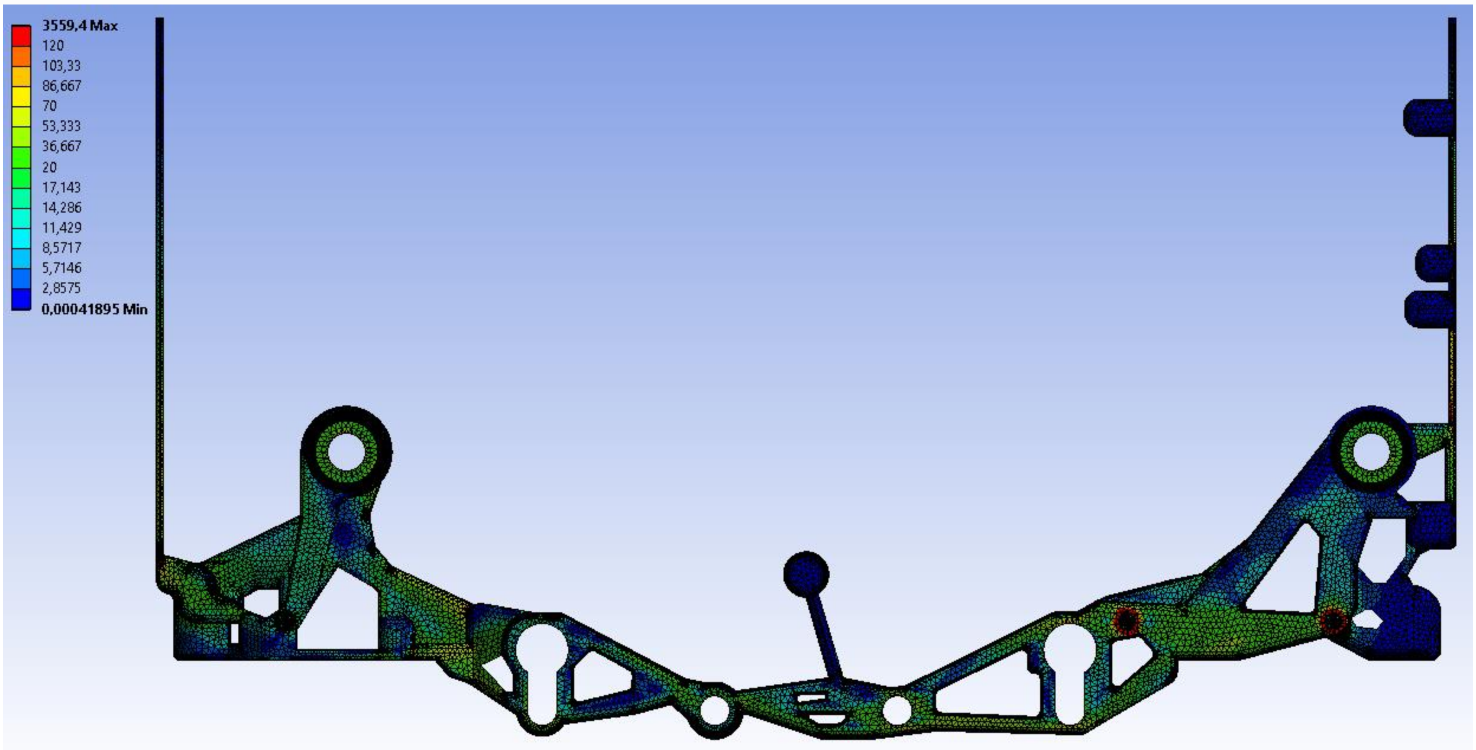


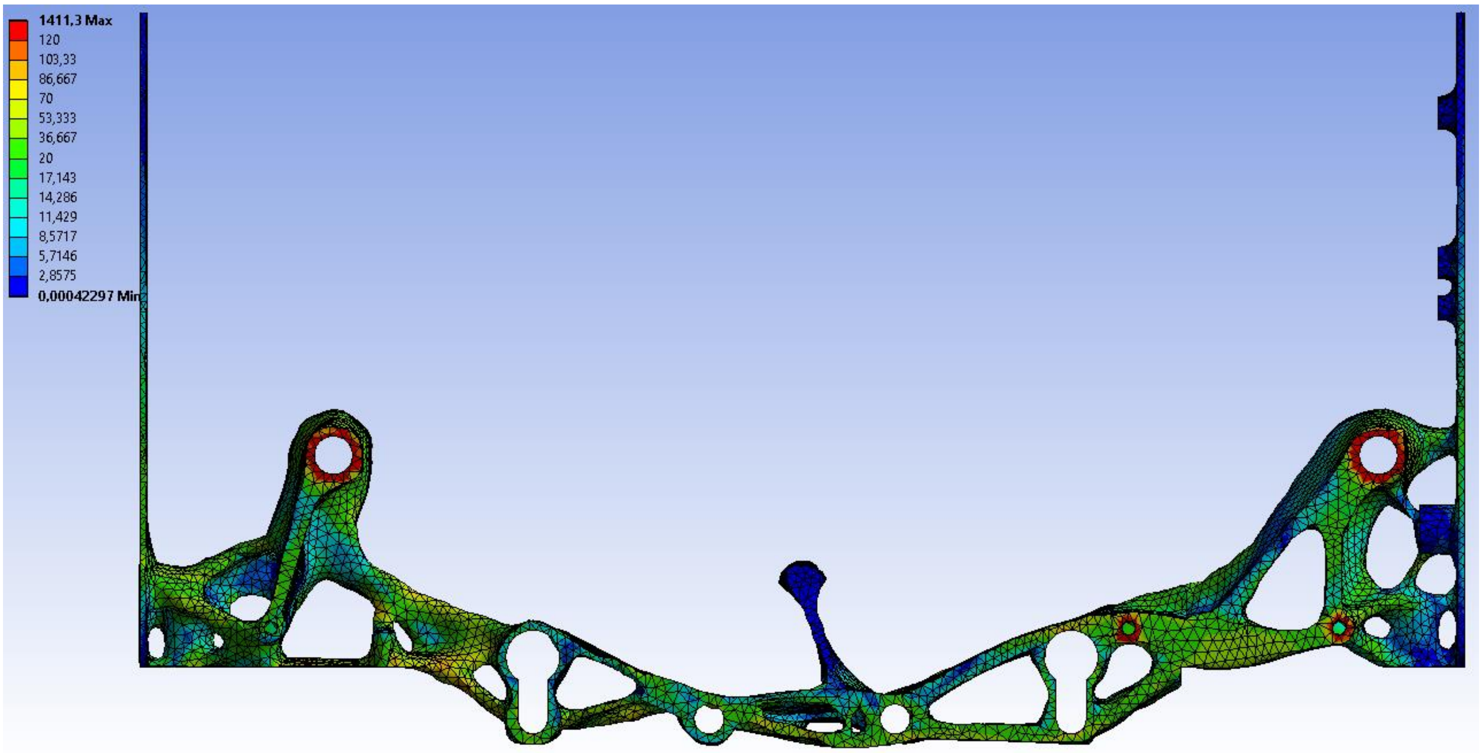

11586 Max
120
103,33
86,667
70
53,333
36,667
20
17,143
14,286
11,429
8,5717
5,7146
2,8575
0,00041923 Min


5396 Max
120
103,33
86,667
70
53,333
36,667
20
17,143
14,286
11,429
8,5722
5,7153
2,8584
0,0014231 Min

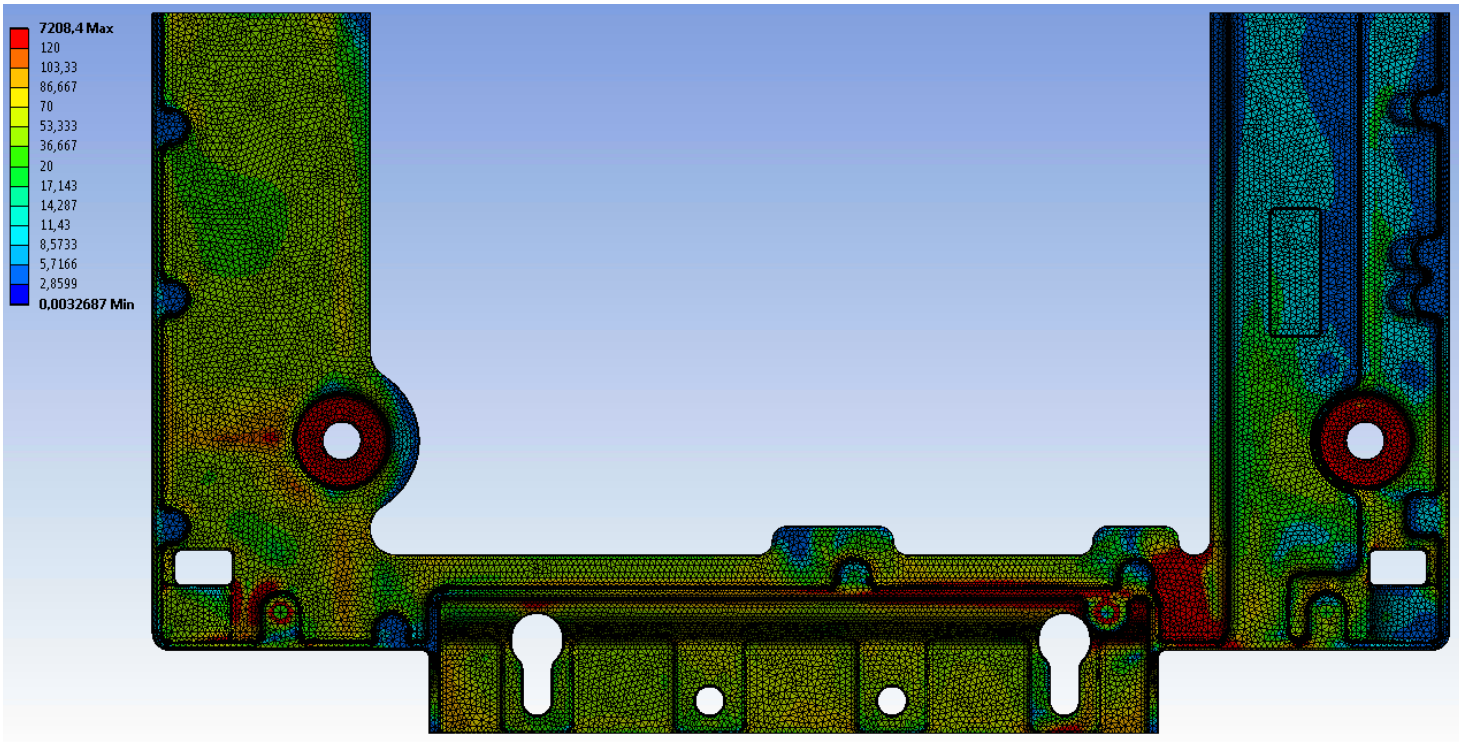
Simulation case: Earthquake X-direction

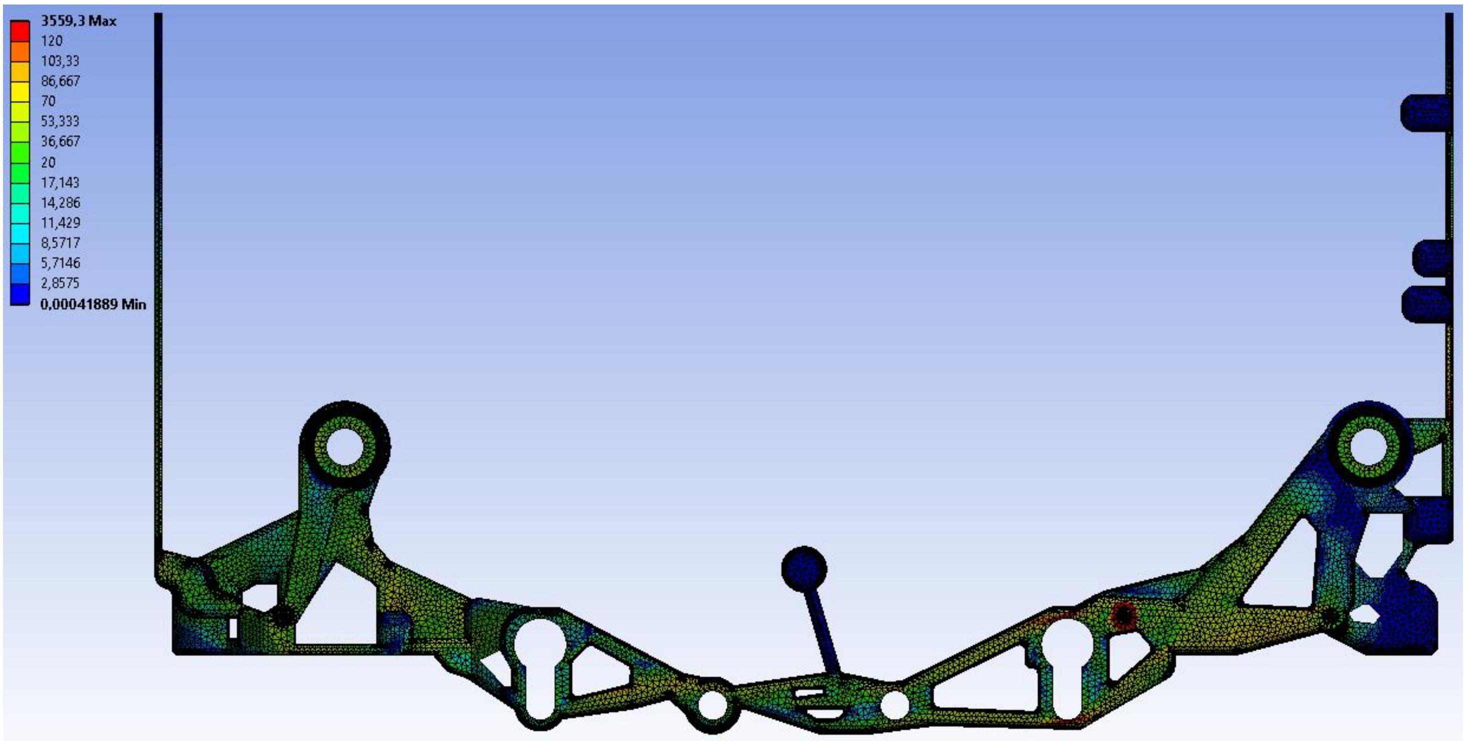


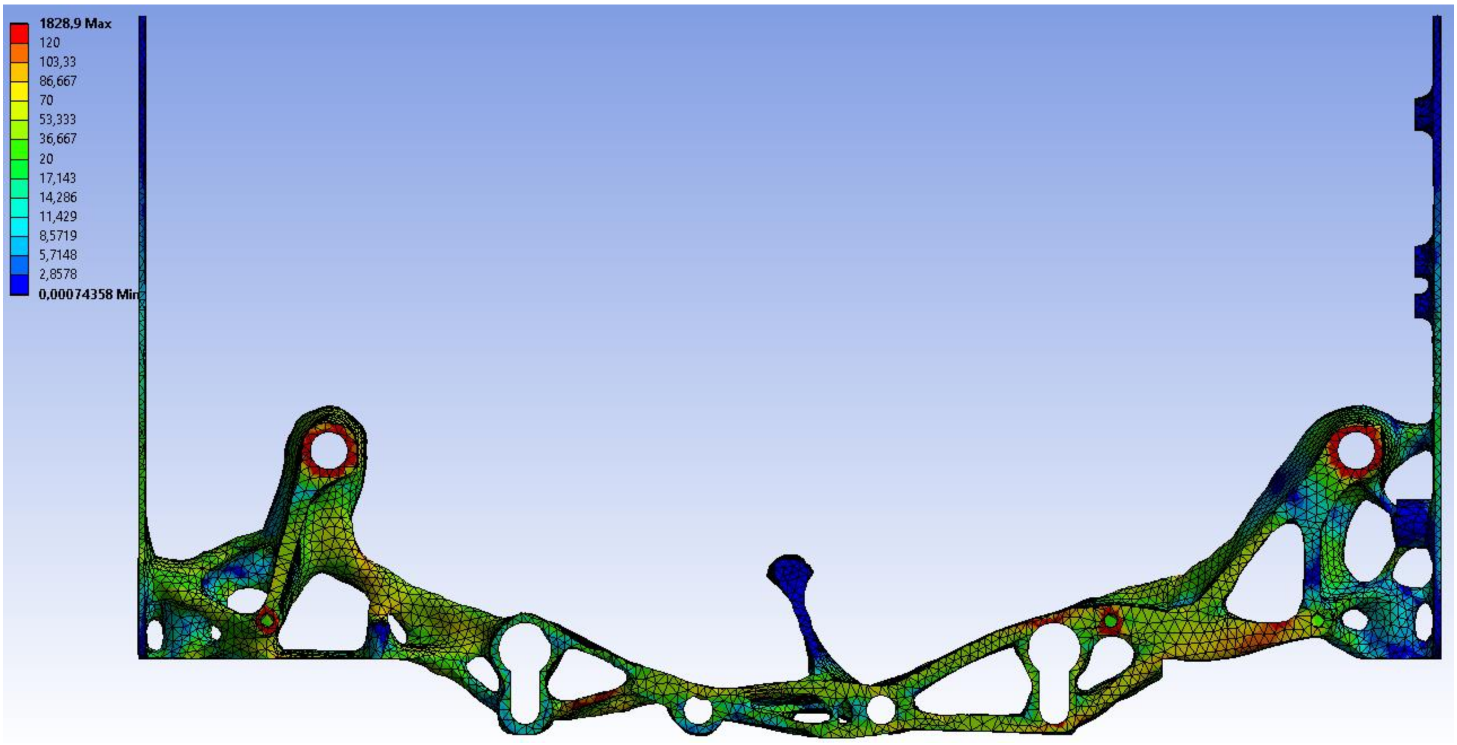




Simulation case: Earthquake -X-direction







When comparing the different designs, it is clear that the skin surface design is the most efficient. It is the lightest one and it does not have any major problems with the stresses. The current design is clearly the worst when it comes to handling loads. This proves the point that even if the design is optimized by hand, it is hard to get as good results as with TO.

There are some issues with the skin surface design from a manufacturing point of view. The geometry is complex, and it is very difficult to create accurate dimensioning. This makes controlling the quality of products slightly harder, especially when talking about pressure casted products whose molds need to be replaced after about 10 000 castings. Currently in the Telecommunications firm, it is required to do a drawing of the product, but doing a drawing and marking dimensioning to it for skin surface design is rather impossible. However, it is reasonable to think that in the future manufacturers will only need the 3d file for manufacturing. As to quality control, a 3d scanner is something that could be utilized there. It would reveal whether the geometry is enough close to what is should be.

4.3.2 Cost savings calculations

Now I will present two different calculations. First, I will tell how much money would have been saved if TO would have been used in the first place. For that calculation I will be using the approximated design which is manufacturable and controllable with current technologies and procedures. The second calculation describes how much could be saved if the skin surface design would be implemented. Because of confidentiality related reasons I can't use actual numbers but instead I will use percentages.

1. Case

Approximated design weighs around as much as the current design and it does not have any geometry that is significantly more complex than in the current design. So, it is reasonable to think that the cost of the approximated design is same than the current design.

Version	Price (%)	2012	2013	2014	2015	2016	2017	2018
101 (1)	100	0	0	0	0	0	0	0
102 (2)	120,2	0	0	0	0	0	0	0
103 (3)	56,1	0,0092	0,012	0	0	0	0,001	0
104 (4)	16,1	2,37	0,062	0,01	0	0,003	0	0
105 (5)	15,5	45,38	1,69	0,004	0	0	0	0
206 (6)	9,1	52,24	98,23	99,98	100	99,99	99,99	100
		100 %	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Table 4. PRODUCT X yearly volumes divided by versions from 2012 to 2018, how much each version contributed to the whole yearly volume.

		Version number						
		101	102	103	104	105	206	
	2012	0	0	0,03	2,86	52,84	44,26	**100%**
	2013	0	0	0,06	0,09	2,31	97,54	**100%**
	2014	0	0,025	0	0,02	0,01	99,95	**100%**
Year	2015	0	0	0	0	0	100	**100%**
	2016	0	0	0	0	0	99,99	**100%**
	2017	0	0	0	0	0	99,99	**100%**
	2018	0	0	0	0	0	100	**100%**
	Total cumulative cost of product lifecycle 2012-2018						confidential information	

Table 5. Total cost of PRODUCT X divided by versions, how much each version contributed to the total yearly cost.

Total cumulative costs generated by PRODUCT X during the time span from 2012 to 2018 has been some tens of millions. Total delivered quantity for that time is some millions of products.

So, if the lighter version had been the first version, cumulated savings from 2012 to 2018 would have been around half a million euros. That may seem a small amount but keep in mind that the data is only available from 2012 and the version 206 was released 2012. For that reason, it can be assumed that if data would have been available from 2006 the calculated cumulated saving would be multiple times larger.

2. Case

Now, the second case is how much could possibly be saved if the skin surface design could be implemented. Best way to approximate the cost of the skin surface design is by weight. The current design weighs 2,65Kg and costs x,x euros per piece. The skin surface design weighs 1,99Kg, so it is 24,8% lighter. Therefore it requires about 24,8% less raw material. The approximated cost is 17% cheaper. (Cost approximation made by Telecommunications firm expert who has been part of creating current design)

Year	Current version price	Skin surface design approx. price
2018	100%	83%

Table 6. Prices for current and improved design

That means that accumulated savings for one year could be as high as some million euros if yearly volumes are enough high or even close to previous yearly volumes. Of course, the development process cost something but the time it would take for me to reach this design is about two weeks, now that I am accustomed to using these software.

As a reminder, implementing casting design this complex would require new procedures and ways to check quality, but if such procedures were to be created, PRODUCT X would be a good candidate for that project.

As a summary, I can say that with high volume products, the use of topology optimization can bring very significant cost savings. In addition to savings in raw material, the correct use of my suggested workflow combined with TO could bring a tremendous efficiency boost to the product development process and therefore generate more cost savings.

5 PILOT STUDY FOR R&D

For this part of the case study I created a totally new pole/wall mounting bracket. Basically, this is a study on how to use TO in R&D rather than in PM. Below is a process chart I created for R&D, and I will explain the process step by step following the presented process flow in the next page.

5.1 Product request

Again, everything starts with a product request which at Telecommunications firm normally comes from product management. They are also responsible for managing the product portfolio. In my case, the product request was for a pole/wall mountable bracket for a radio product that weighs approximately 70 Kg.

5.2 Product requirements

Next, there was a meeting where the initial requirements were set. In R&D, the requirements are not as clear as in PM, but some requirements must be defined for the project to move on. What happened during this case study was that the requirements changed a few times which caused quite a lot of extra work and therefore I suggest in my project chart to define them as well as possible from the beginning. The starting requirements were that the bracket must turn horizontally from -30 degrees to +30 degrees, and vertically from -15 to +15 degrees. Manufacturing style was to be AM and material aluminium alloy AlSi10Mg. Initial radio weight was set at 70Kg and it was said to have certain outer dimensions. The weight changed to 40Kg after I had done the initial topology optimization and the outer dimensions of the radio changed much later which then forced me to modify the design at very late stage. This is why I suggest that when developing mechanical parts, especially brackets, the following requirements should be agreed upon and documented:

- Weight the bracket must carry
- Outer dimensions of the product it carries
- Functionalities, such as tilt angles
- Fixing points

- Possible dimensions of how far the product must be from a pole or a wall etc.
- Usable design space
- Manufacturing style
- Weight of the bracket
- Price
- Material/environmental requirements

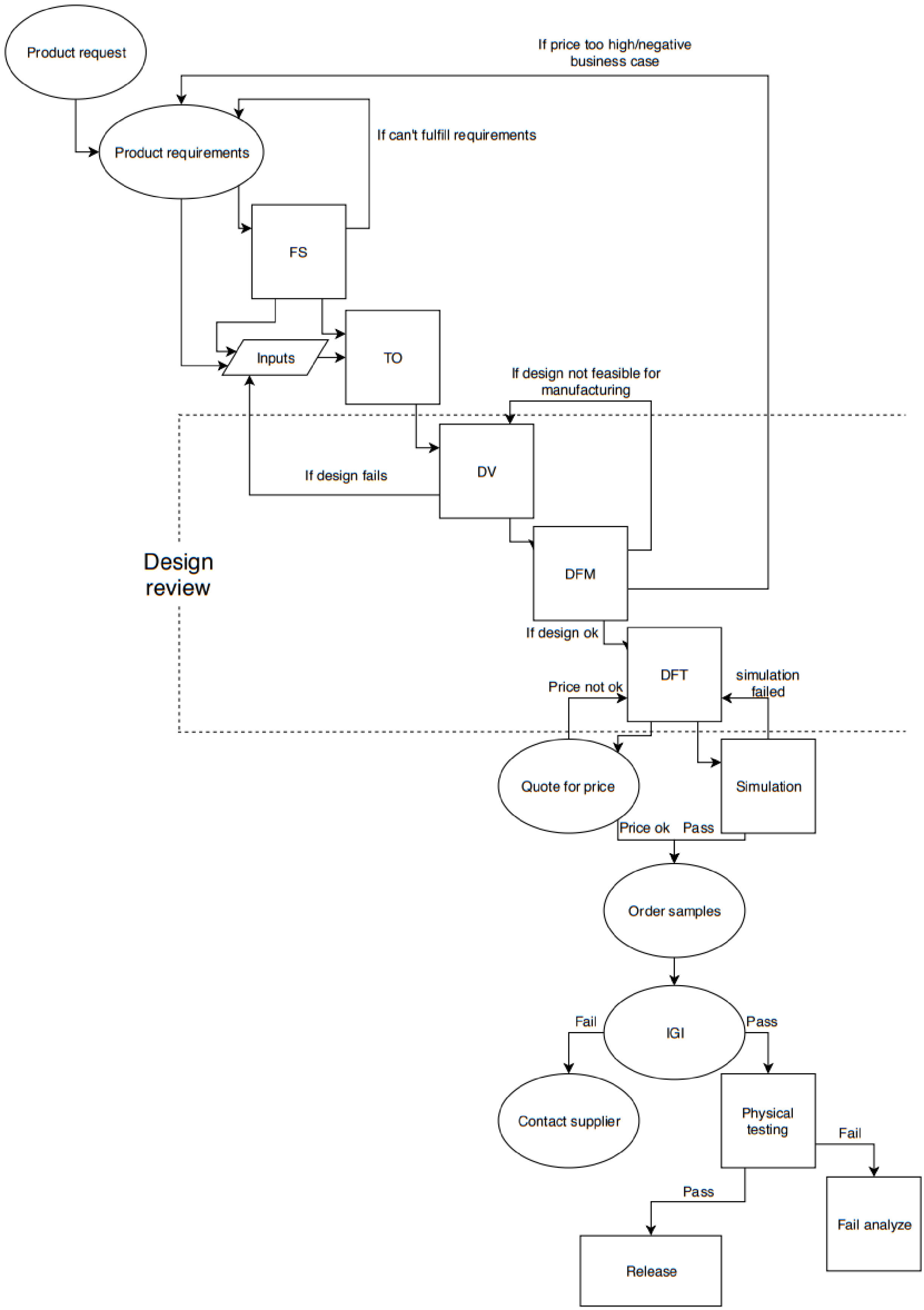


Figure 38. Process chart for mechanical R&D

5.3 Feasibility study

After these requirements, or at least as many as possible, have been documented the process can move on to the next step which is feasibility study. The point of the feasibility study is to create a concept of what the product could be like, so it would fulfill the given requirements within the given budged. As in the product which I designed during this case study, the concept of how to achieve the tilt angles should be defined at this point as topology optimization can't really help with that. During the feasibility study, first estimates of a possible price for the product should be calculated. If the price seems to rise too high then, for example, product requirements should be changed, or the whole project possibly ended as unfeasible. To put it briefly, the point is to see if the product is feasible to design and manufacture.

In my design work, the feasibility study included creating concept ideas on how to realize the tilt angles with as good efficiency as possible, and how many parts it would require to work. At this point we chose to utilize a joint design that was successful in another bracket. In this project the required production method was chose to be AM which meant that there are little to no restrictions on the geometry of the design. After the design was deemed feasible, the process moves on to the next step. To summarize, the following should be known after a feasibility study:

- How to fulfill requirements within the given budget
- A concept of how to realize required functionalities
- Starting weight for the TO (input for TO)

As after all steps, proper documentation is advised to make sure everything is in order and that all participants know what is happening.

5.4 Topology optimization and Design validation

Finally, after the feasibility study it is time to move on to TO. The design validation step is highly intertwined with TO, and that is why I will go through them in one sub chapter. TO and DV include many different steps in themselves, and to make it clearer, I have constructed a process flow for the two. I presented it in the previous part of this thesis but as a reminder it is also presented here. I will go through the TO and DV process again, because for a completely new product it is a bit different, and because after seeing two different cases of TO it's easier to see what really carries weight during the process.

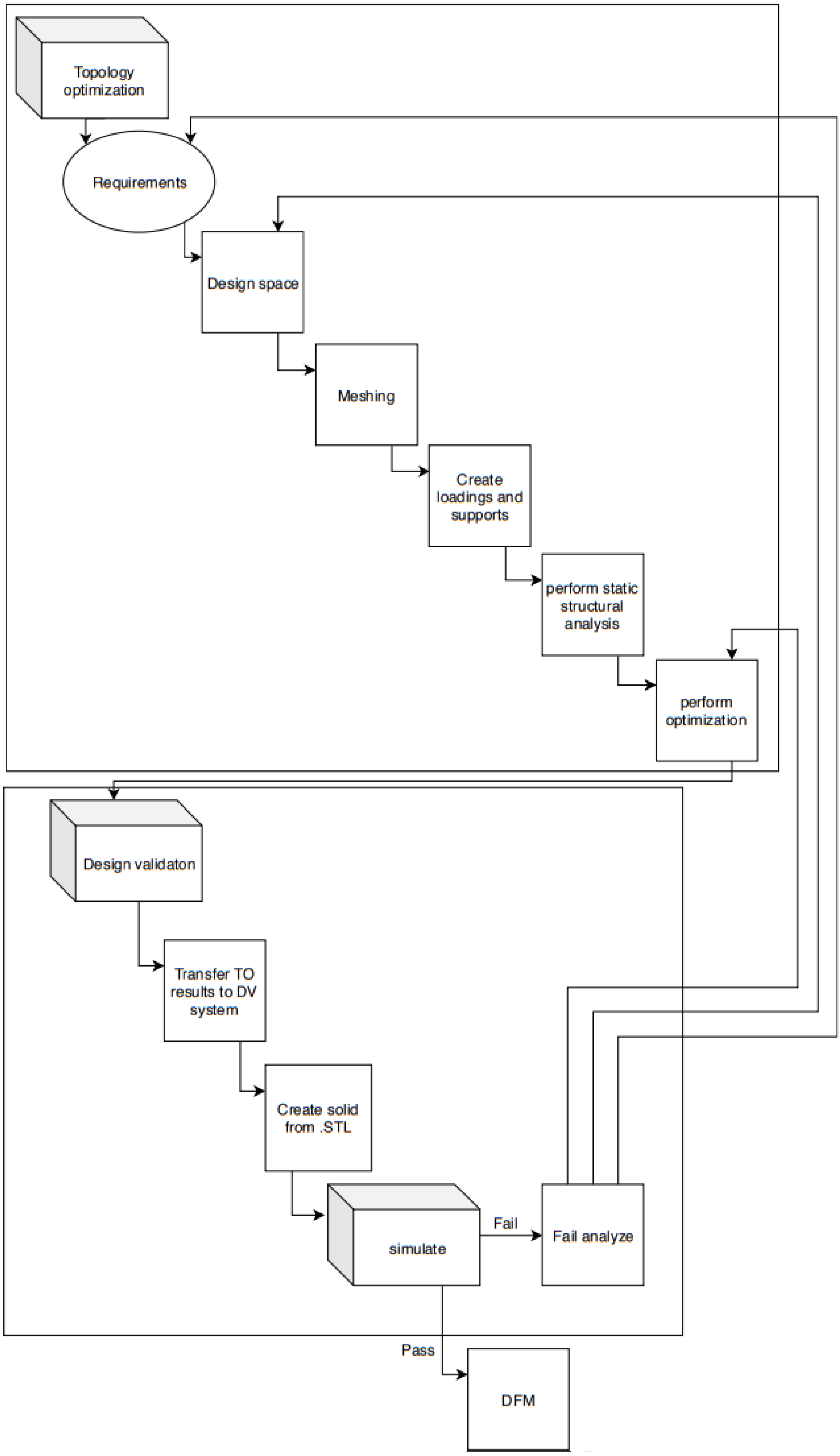


Figure 39. Topology and design validation process flow

As before, TO starts with requirements that should be available in the product requirements document and the feasibility document. The next thing is to create a design space. Or, in this case, three design spaces, since the main assembly is constructed from three different parts. In this case I performed the optimization on all three parts at once

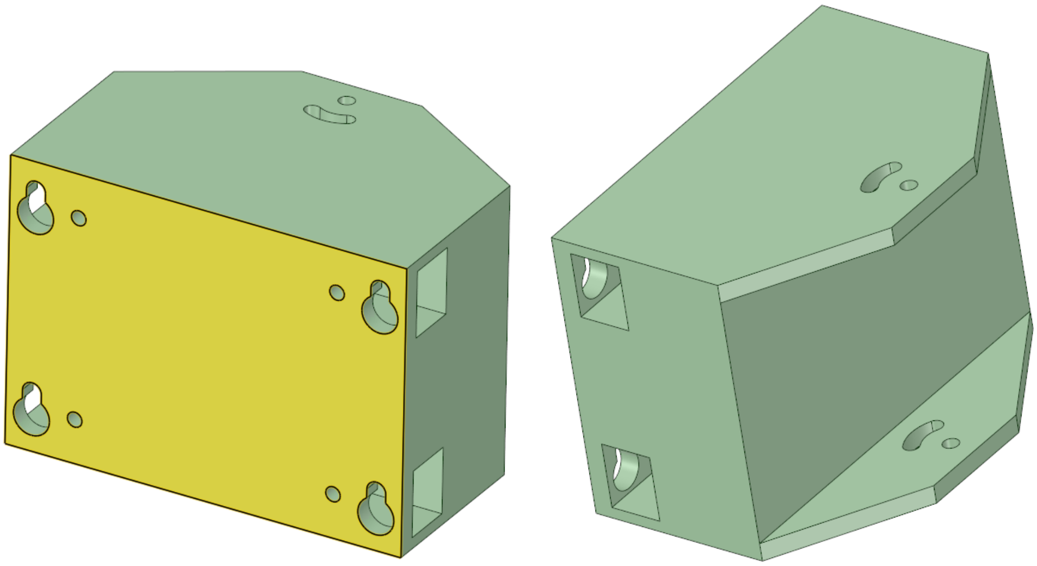


Figure 40. Design space for pole side part

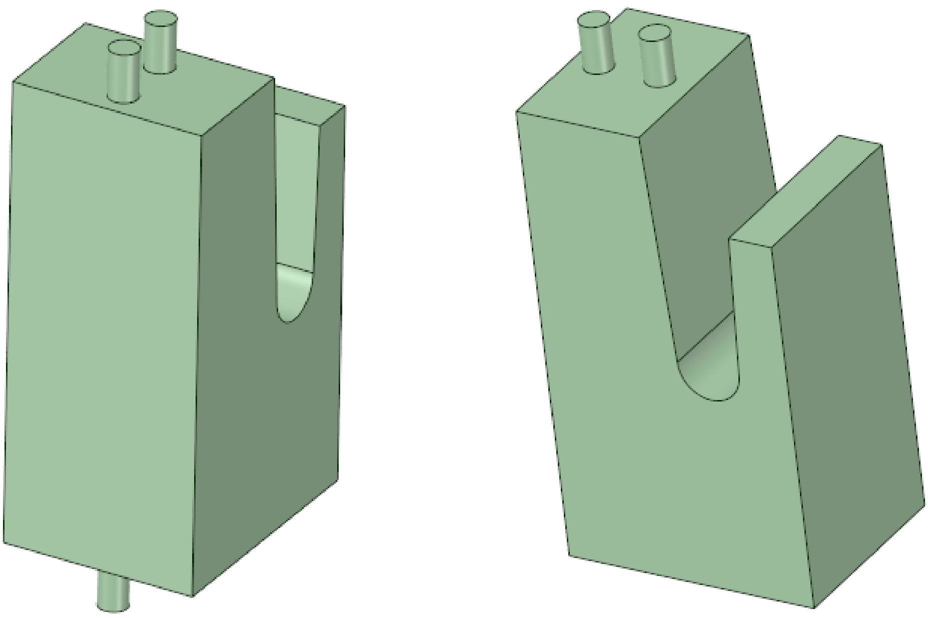


Figure 41. Design space for the middle part

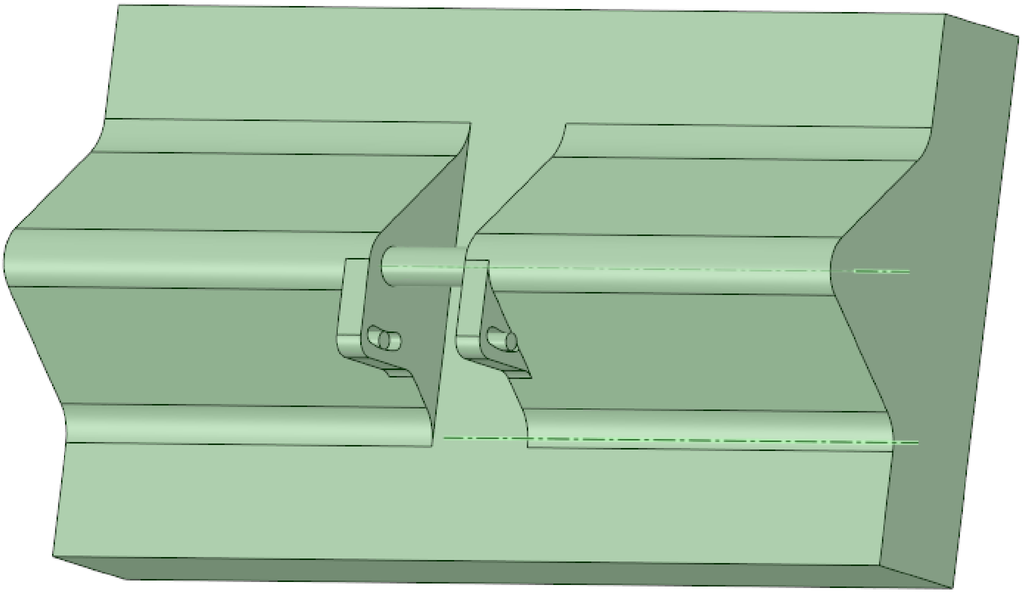


Figure 42. Design space for the radio side part

For these design spaces I have constrained surfaces between the different parts to assure that the tilt angles also work after optimization.

The next phase is meshing. As stated earlier, creating a mesh that is dense enough but not too dense is important for getting adequately accurate results without using too much time. Below are the design spaces assembled and meshed.

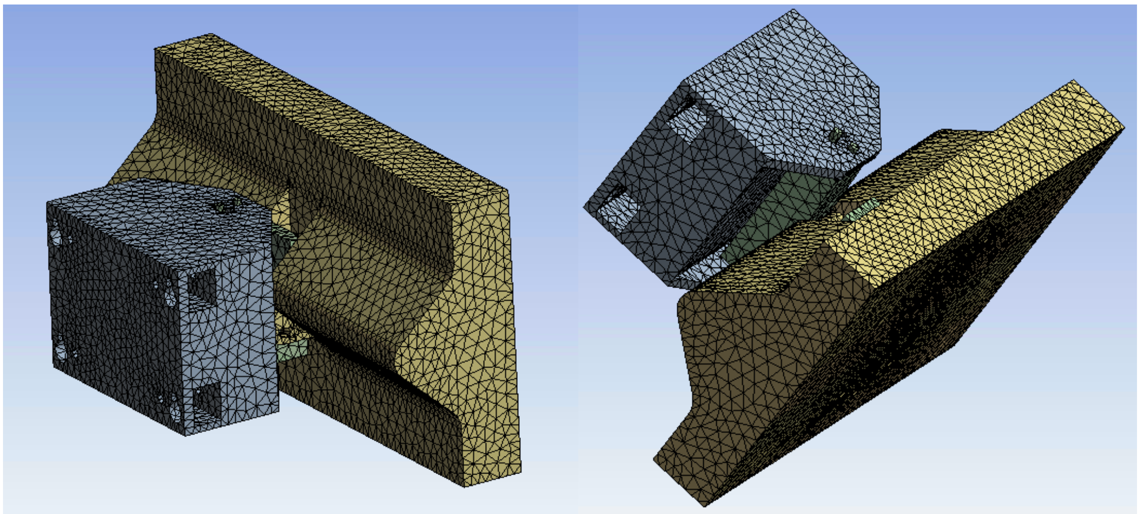


Figure 43. Design spaces assembled and meshed

For this optimization I did not use as dense a mesh as for the PRODUCT X optimization, because the optimization would have taken too long compared to the benefits it gives.

The next phase is to build static structural loading cases. Now, as this is a completely new product that has no limitations on, for example, how it attaches to the product, creating loading cases such as in the PRODUCT X case is impossible. That is why in this case I used accelerations and wind load as loadings. From previous testing and designing of other products it is known that earthquake test is the one that almost always creates the most stresses. Maximum acceleration in earthquake testing is 50m/s^2. Wind load is calculated with the below formula. But, in any case, the minimum wind load is to be 450Nm, according to the used standard.

So, I created total of six loading cases, wind loading for each axis and acceleration for each axis. As the product must be symmetrical, it is enough to have accelerations and wind loads only to the other directions.

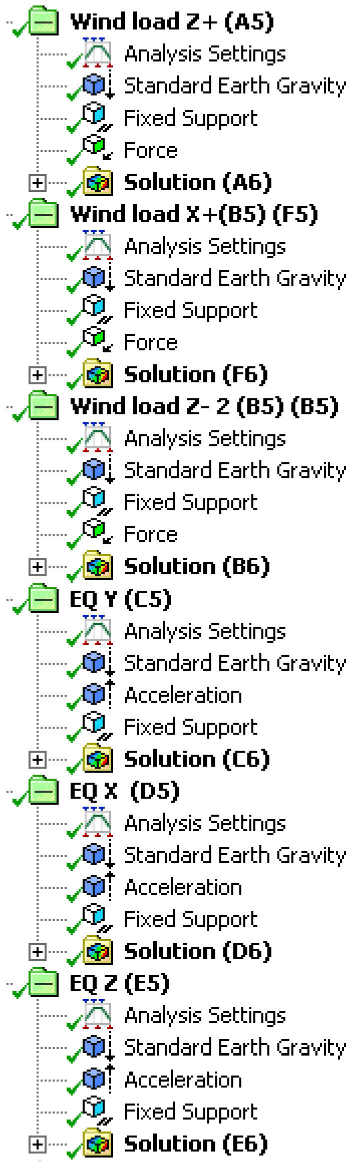


Figure 44. Load cases for topology optimization

After solving the static structural analysis, it is possible to move on to setting up the actual optimization. One must define the optimized region, retained weight (if minimize compliance solver is used) and possible manufacturing limitations. For my optimization I used minimize compliance, weight retained at 5% and symmetry manufacturing constraint.

After the optimization is complete, it is time to move on to the design validation step. It starts by moving the topology optimization result to the design validation system. This has been made easy in Ansys workbench, so it can be done just by clicking transfer to design validation system. After that it is time to start forming solid parts from the STL files.

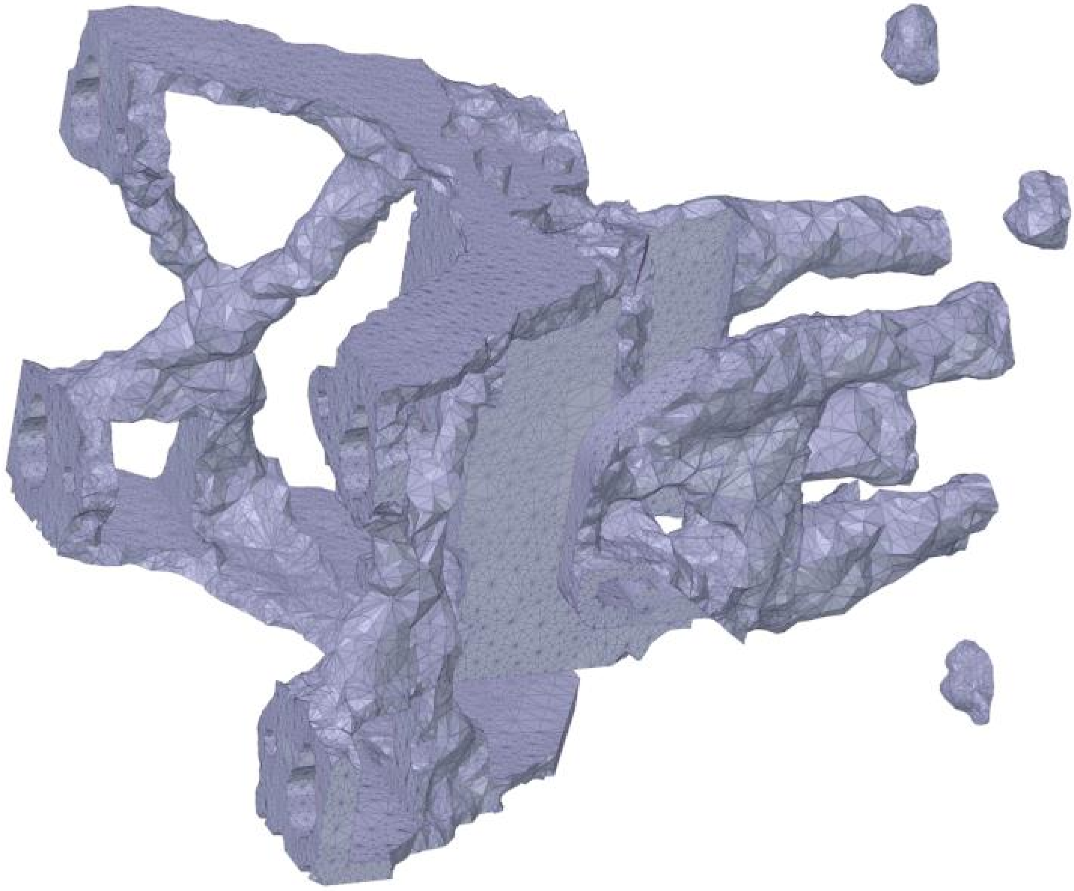


Figure 45. Result of TO

When forming solids, easiest way is to start with smoothening out the STL file. Simplest way to do it is to utilize spaceclaim’s automatic tools such as shrinkwrap and smooth.

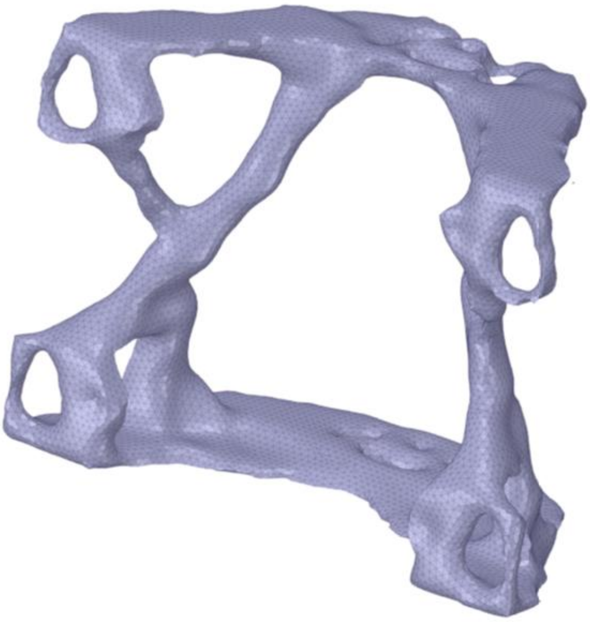


Figure 46. Pole side part after smoothing operations

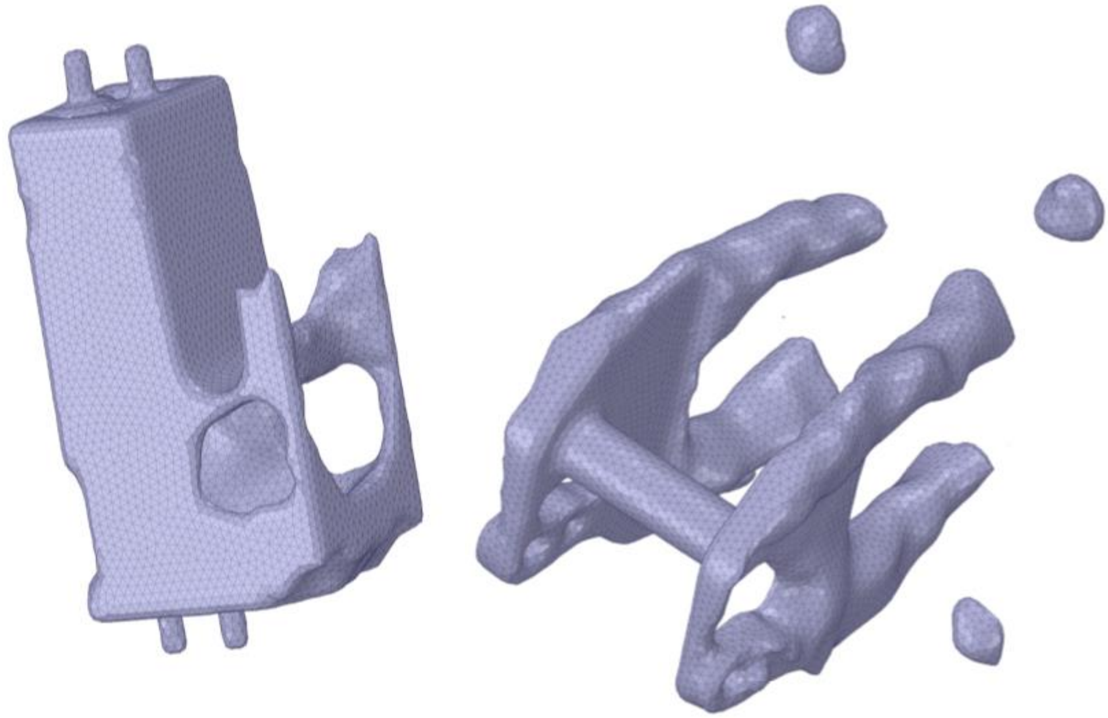


Figure 47. Middle part and radio side after smoothing operations

Doing these smoothening operations takes some minutes, in this case close to 10 minutes. After the smoothening there are few different approaches which were explained earlier in this work. As discovered earlier, the simplest way to move forward from this point is to use the original design space and cut material out from that to form a solid that resembles these TO result STL files. When the solids are ready, it is possible to move on to the simulating phase, as the process chart shows.

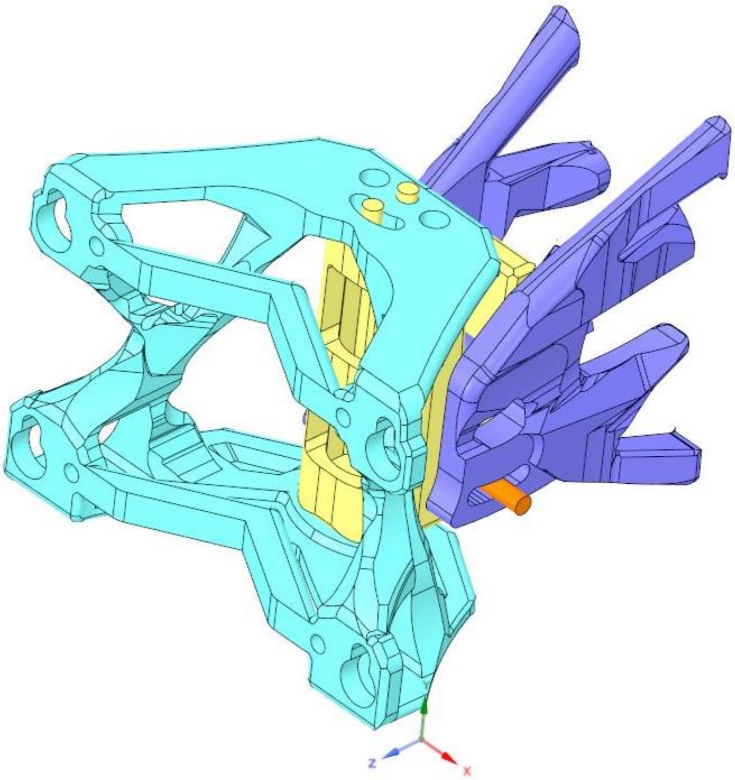


Figure 48. Solids for first simulations

When simulating at this point, it is possible to use same static structural analyses that were used for the optimization. The idea is that these analyses will give some information about the functionality of the design.

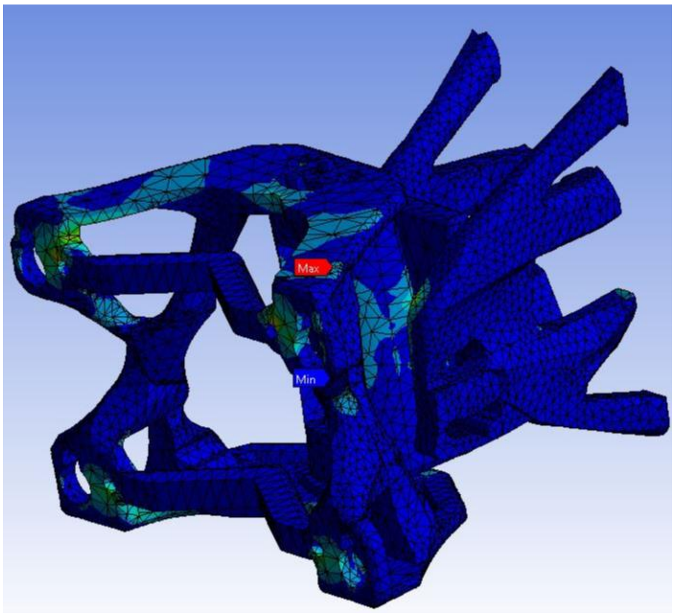


Figure 49. Result of design validation simulation

5.5 Design fine tuning and DFM

In this case, the simulation showed that the design is feasible. Next phase, according to the process chart, is DFM and design fine tuning. Design fine tuning is the only phase where the designer really affects how the product will look. Depending on the product and the requirements for its design, fine tuning can take quite a lot of time. I consider it to be the most cumbersome phase.

When it comes to DFM, its importance depends quite a lot on the chosen manufacturing method. For this part the chosen method is AM, and therefore DFM is a simpler process than, for example, if the method would be die casting. In DFM discussions, only one design change was suggested.

After the design has been fine-tuned it must be simulated again, this time more thoroughly. If everything goes perfectly there will not be any loop between fine tuning the design and simulating it, but in reality, there will be a few rounds of designing and simulating. The amount of these rounds, in my experience, depends on how close to the lightest possible product the designer wants to go.

5.6 Simulating

After design has been fine-tuned it must be simulated to make sure it can take all the forces without braking. These simulations can vary depending on the environmental requirements. For example, pole brackets, such as the design I created, must withstand vibration load and earthquake induced forces, as well as wind load.

Since the idea of this thesis is not to focus on the simulation part, I will only go through them in a simplified manner.

Wind load, meaning the force generated by wind, is a simple linear simulation that is easy to set up. The amount of wind load depends on the outer dimensions of the product and it can be calculated the following way:

$$P = 0.10\,WH$$

Where:

P = Force, lbs.

W = Product width, inches.

H = Product height, inches.

(GR-3178-CORE, 2014)

More sophisticated simulations such as vibration and earthquake need more work. In total, four different simulation cases need to be tested: wind load, shock, earthquake and random vibration. All but wind load are dynamic loadings and the forces must be described using time and acceleration. In Ansys workbench these can be simulated by using Response Spectrum. All these dynamic simulations need modal analysis as a basis. A modal analysis tells the eigenfrequencies of the product. In Telecommunications firm the lower limit for acceptable design is 6Hz.

Frequency	Acceleration (mm/s^2)
0,3	2000
0,6	20000
2	50000
5	50000
15	16000
50	16000

Table 7. Earthquake simulation inputs

Frequency (Hz)	Acceleration (mm/s^2)
5	2500
10	40000
50	40000
100	2500

Table 8. Random vibration simulation inputs

Time (s)	Acceleration mm/s^2
0	0
0,00025	3566,96
0,0005	7115,74
0,00075	10628,26
0,001	14086,63
0,00125	17473,21
0,0015	20770,75
0,00175	23962,45
0,002	27032,04
0,00225	29963,88
0,0025	32743,04
0,00275	35355,34
0,003	37787,48
0,00325	40027,06
0,0035	42062,68
0,00375	43883,95
0,004	45481,60
0,00425	46847,49
0,0045	47974,65
0,00475	48857,34
0,005	49491,07
0,00525	49872,61
0,0055	50000,00
0,00575	49872,61
0,006	49491,07
0,00625	48857,34
0,0065	47974,65
0,00675	46847,49
0,007	45481,60
0,00725	43883,95
0,0075	42062,68
0,00775	40027,06
0,008	37787,48
0,00825	35355,34
0,0085	32743,04
0,00875	29963,88
0,009	27032,04
0,00925	23962,45
0,0095	20770,75
0,00975	17473,21
0,01	14086,63
0,01025	10628,26
0,0105	7115,74
0,01075	3566,96
0,011	0,00
0,06	0,00

Table 9. Shock simulation inputs

When creating these simulation cases, a direction must be set and because of that, a simulation must be created for every axis (X, Y, Z). For this bracket, there are quite many simulation cases because it has many different installation orientations and all of them need to be simulated. In this case the total amount of simulation cases is 72.

If the more sophisticated simulations also show that the product can handle the needed loads, a sample can be ordered if the quoted price is in line with the product requirements.

5.7 Sample inspection

After ordering and getting the samples it is possible to begin physical testing/verification. It is mandatory to test the samples successfully before the product can be released for mass production. Physical testing includes vibration, usability and earthquake testing.

After these tests have been completed and passed, the product can be released for mass production.

6 LESSONS LEARNED FROM PILOT STUDIES

When starting this thesis work, I had no previous experience on designing or developing mechanical parts. This might have been beneficial since it also means that I did not have a prior mind-set, but was open to try to take full advantage of the software.

Some key things I learned from the case study are the following:

- More defined requirements = more straightforward process → faster developing process overall
- Less defined requirements = more design freedom →possibility of having to redesign after new requirements surface → slower development process
- More design freedom gives possibility to fully exploit TO
- TO accelerates design process since there is no need to start from an "empty table", first designs for review can be ready in less than two days
- With complex products, the designer must come up with the concept on how to achieve some requirements, for example tilt angles
- Careful meshing makes a big difference for the better, in optimizing and simulating

In topology optimization, as in any other process, there seems to always be a tradeoff between certain things. For example, my research and trials show that it is not feasible to have the lightest possible product if certain planes are constrained or forced to remain untouched, which is rather obvious. Other clear tradeoff is time and accuracy. It's possible to have results from TO very fast but that is done on the expense of accuracy. Then again, it is not efficient to be so accurate that it raises the development time manifold.

When discussing development time, the most time-consuming thing is having to redesign. To avoid it, the needed requirements should be discussed and decided upon as early as possible, whereas in R&D it is quite natural that requirements are refined during the project. A good rule of thumb here is that the later more requirements arise or existing ones change, the more time has gone to waste. When designing with TO and when the goal is to reach the optimal solution, even slight changes might mean that it's necessary to go all the way back to TO in the process. This might sound bad but here it is important to remember that changing some parameters in TO only takes some minutes and the benefit gained may be significant.

Manufacturing method has significant impact on the result of optimization and that is why, earlier in this work, I went through the main manufacturing methods. All manufacturing methods have their disadvantages and benefits. During my research it became even more clear that only way to achieve truly optimized geometry is by AM, so the result matched my hypothesis. The fact is that how complicated the loading cases are has a big impact on how much difference there is between, for example, a casted and a printed part. Normally the goal is not to solely to reach an optimal weight–strength ratio, but rather to achieve the best price–weight–strength ratio. Basically, this means that AM is not often more optimal than casted design when cost is considered. In short, one must contemplate between different goals and choose the most suitable compromise.

7 SYNTHESIS OF THE RESULTS

As mentioned earlier, the results of this thesis include a process chart for PM and R&D, a demo product for PM, a demo product for R&D and implementation suggestion.

7.1 Process chart for Product Maintenance

I created this process chart after doing trials and my research on TO, as well as product development. Basically, this process chart considers every possible thing that could happen during cost reduction or quality improvement project.

I desired to create this process chart to make it clearer what needs to happen and in what order to realize the full potential of TO. The setup of this process chart differs slightly from a regular process chart. I have combined this chart with the stage-gate system, which means that at every gate there should be results that are properly documented. The idea for this rose from the apparent communication problems between different organizations during development which can lead to pointless work. All in all, this chart is fairly simple since CR/QI projects are quite straightforward.

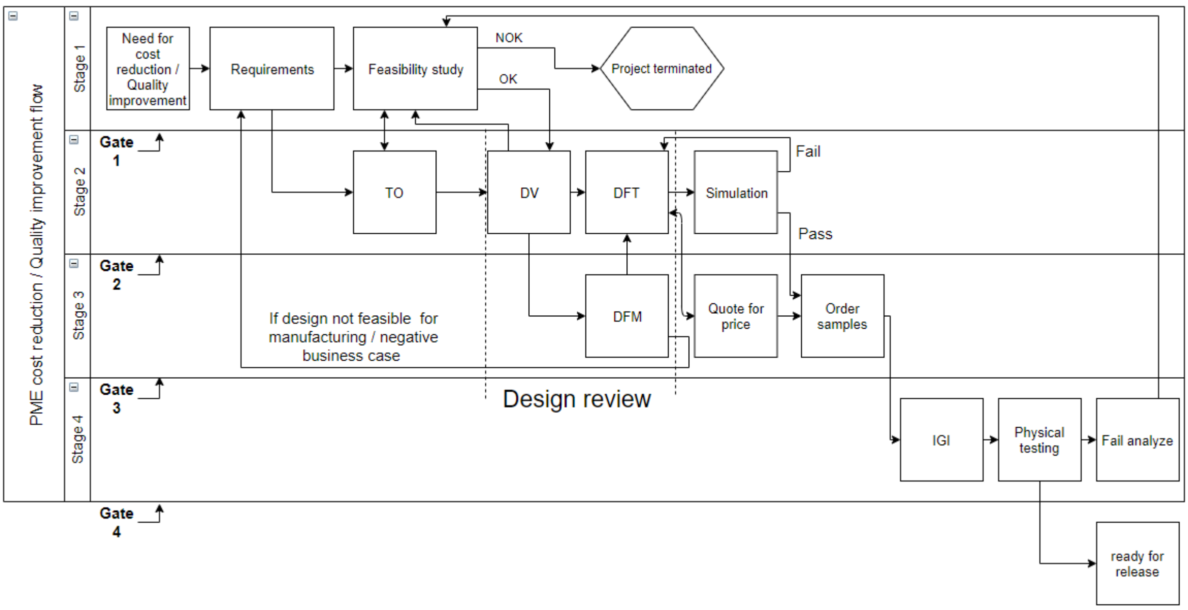


Figure 50. Process chart for PM

7.2 Demo product for Product Maintenance

For PM, I created two different versions of the same product, one a bit more ambitious and one that is feasible for manufacturing even with current policies.

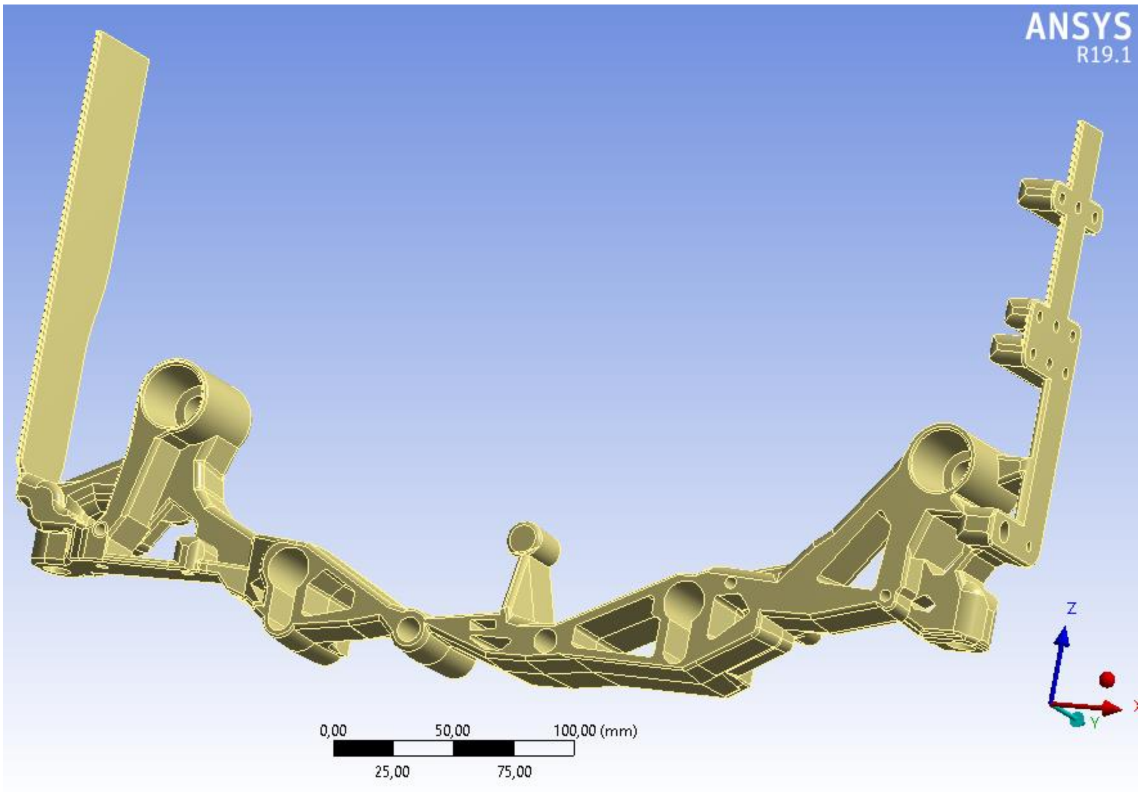


Figure 51. Feasible design for currents policies, earlier referred as “approximated design”

The development time for these two versions was two months. The development of the currently used version took about six months, so I was able to cut development time significantly, by about 65%. These products have not yet been tested physically, but the simulations show that my designs should be much stronger compared to current design, and the current design has obviously been tested.

To put it briefly, the result of this demo case was that I was able to cut development time by about 65% and weight for the other design by about 25%. The design shown in the picture above weighs as much as current design. Both my designs show superior performance in simulations, when compared to current design. Since my designs do not suffer from concentrated stresses, it is feasible to assume that my designs would last longer and therefore their quality is better. The results of the simulations can be seen earlier in this work.

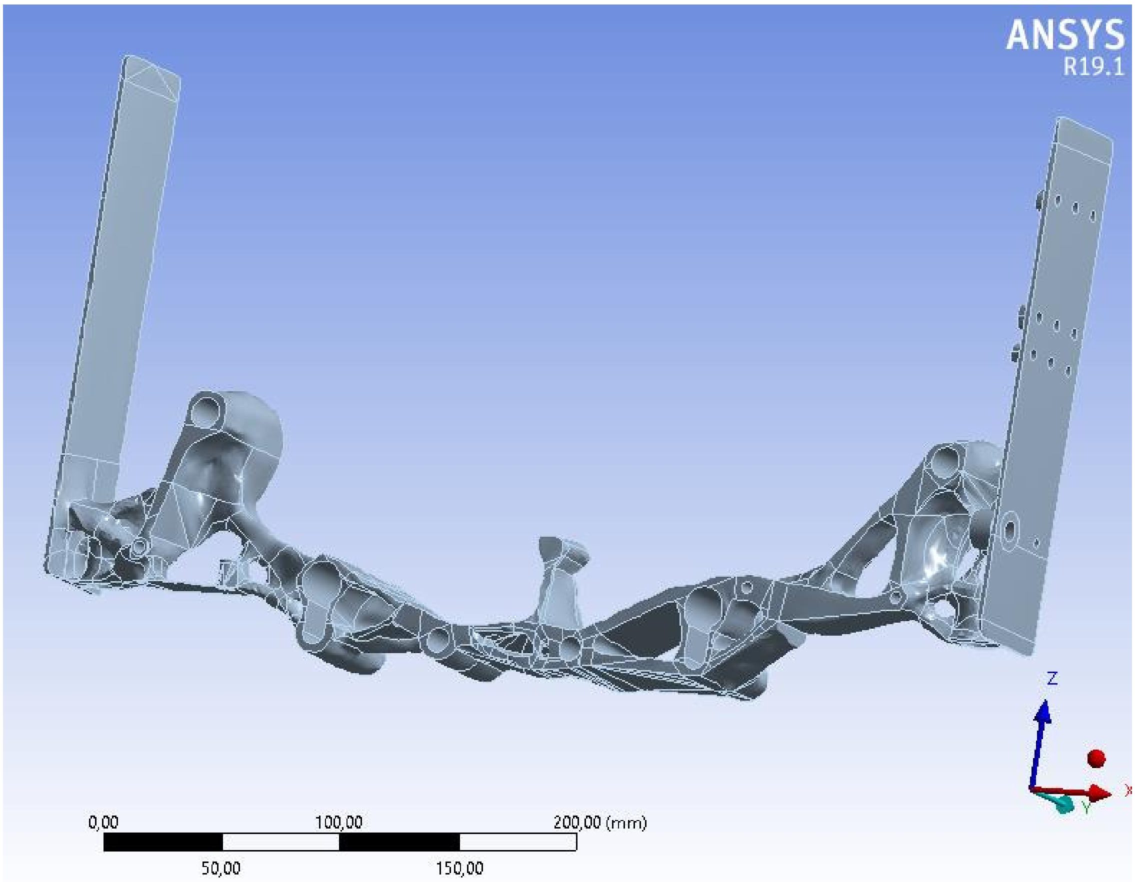


Figure 52. Working design, implementing would require new policies for dimensioning etc.

7.3 Process chart for R&D

I wanted to create a totally different process chart for R&D since my trials and development of the demo product showed quite unambiguously that the process of creating totally new design differs significantly from creating designs for a cost reduction or quality improvement project.

The biggest difference when creating something totally new, compared to improving an old product, is that there is no way of knowing everything from the beginning. Often there are things you do not know and things you don't know you don't know. The latter are usually referred as unknown unknows. This causes uncertainty that must be accepted. Also, it leads to the fact that this chart has more loops in it. Both created charts have in them TO and DV phases witch I opened more in their own chart for clarity.

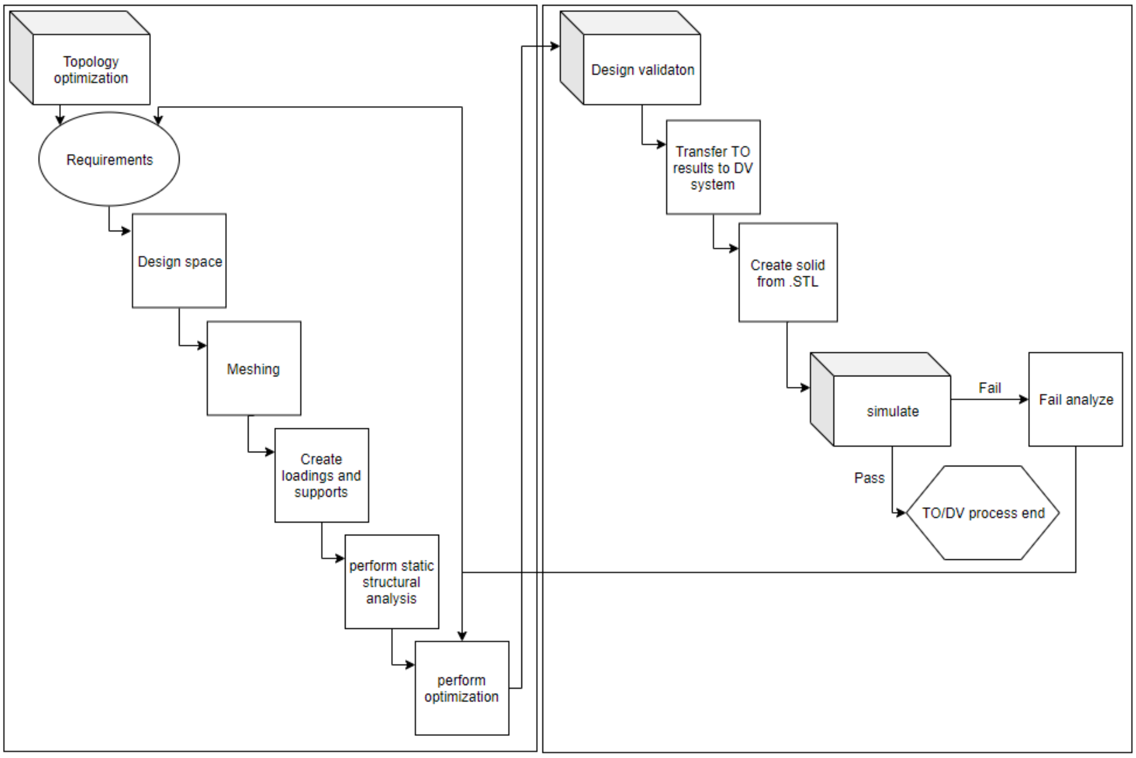


Figure 53. Process chart for TO and DV

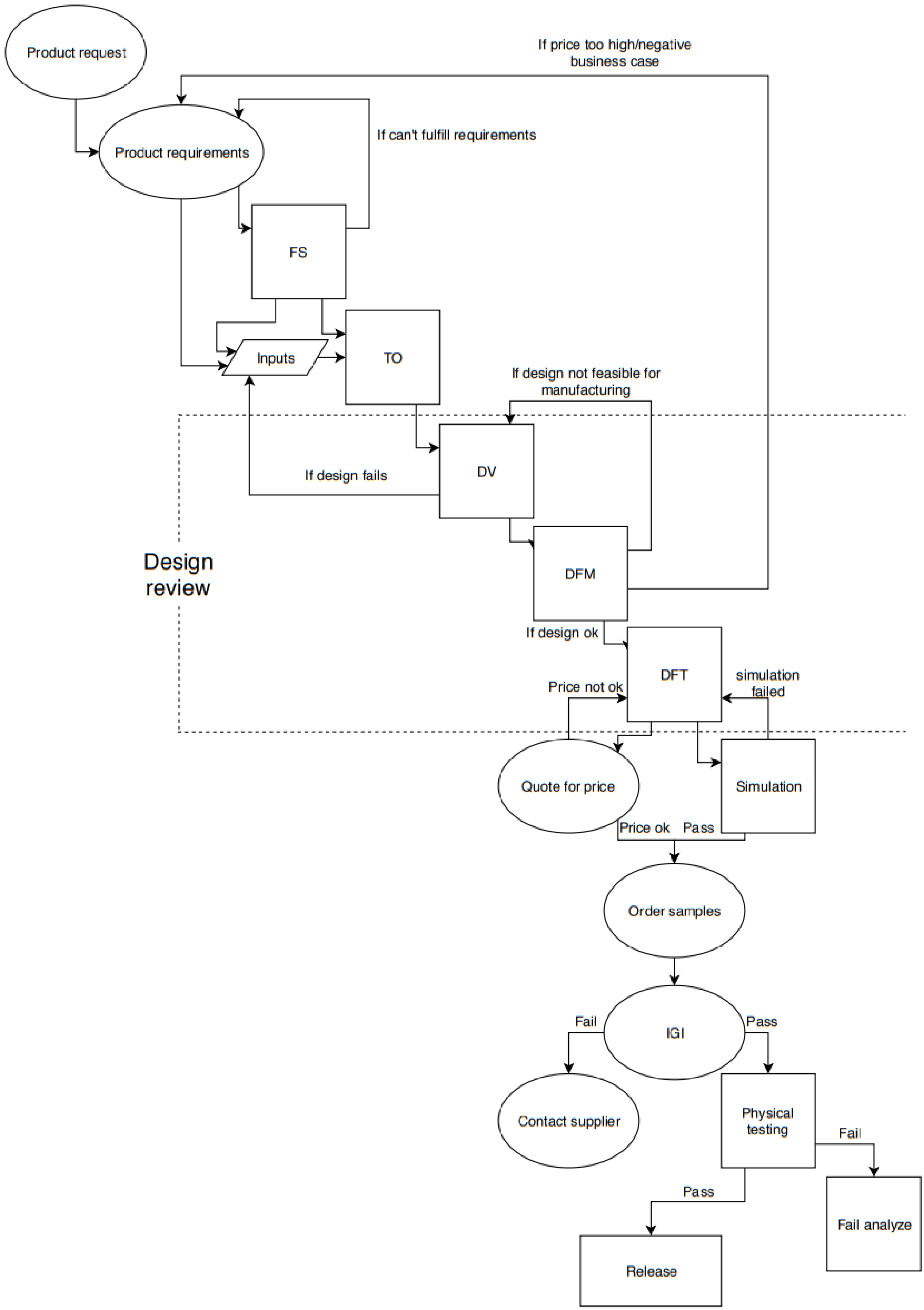


Figure 54. Process chart for R&D

7.4 Demo product for R&D

For R&D I created three different versions of the same products, the development of the first one is described step by step earlier.

First version (Version 1.) was designed to support attachment to wall and poles from 60mm to 120mm diameters and it was designed to carry 40Kg. Next version (Version 2.) had the same requirements, but it only had to carry 25Kg. The third version (Version 3.) also had to carry 25Kg, but it must also support pole sizes from 30mm to 120mm and L-bar fixing.

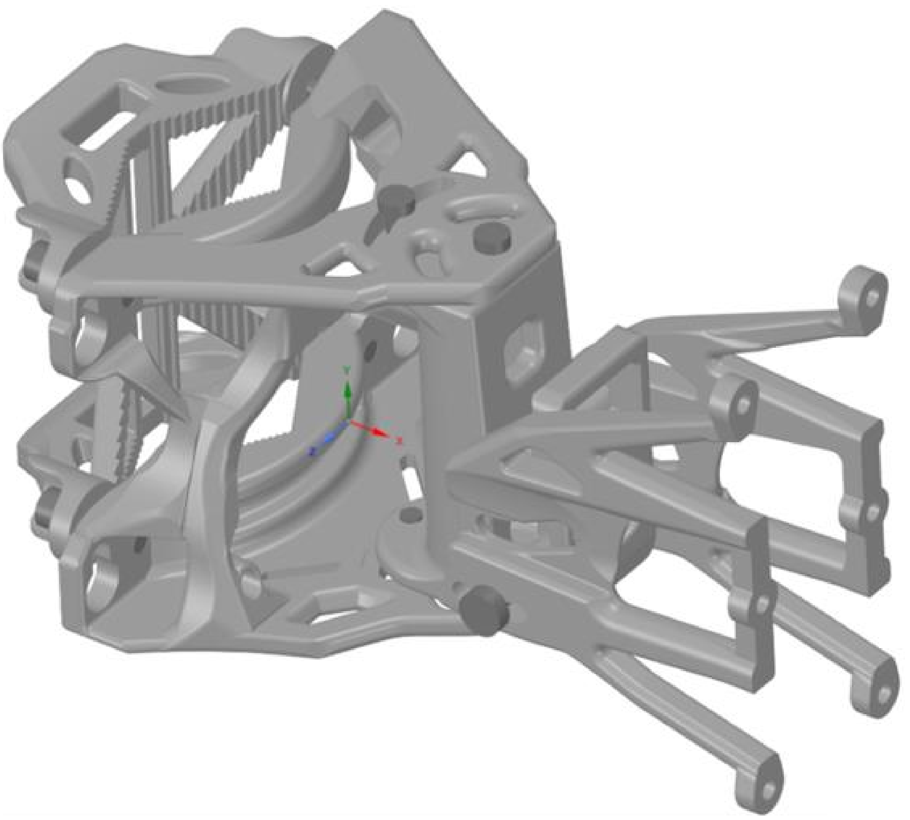


Figure 55. Finalized design for version 1.

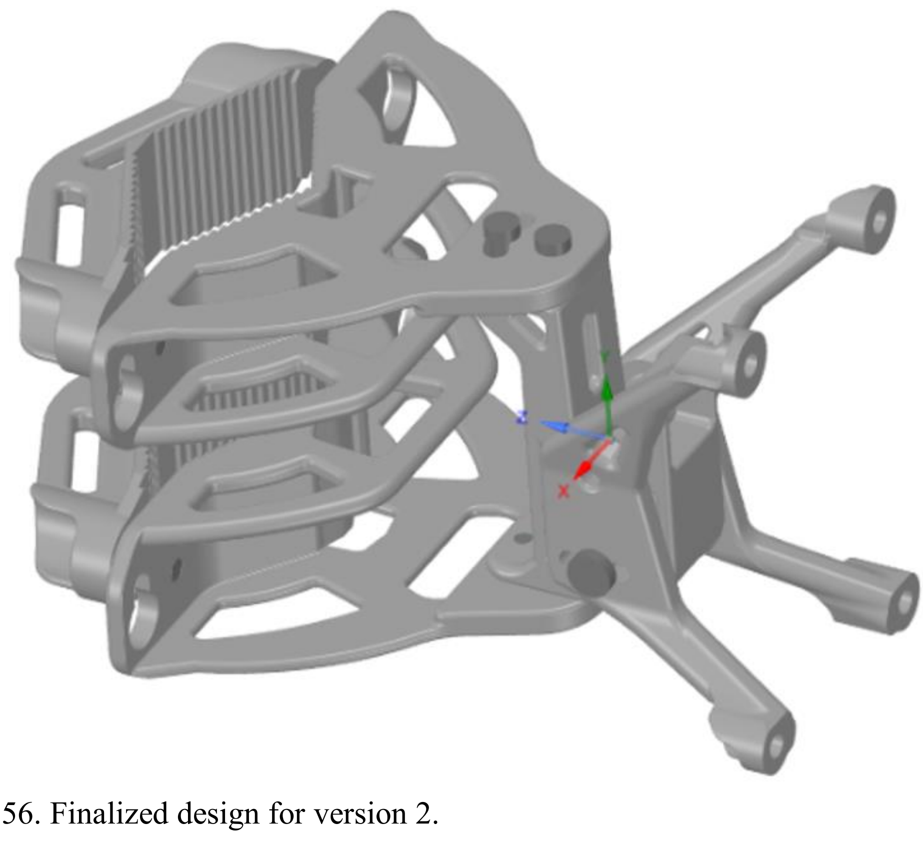


Figure 56. Finalized design for version 2.

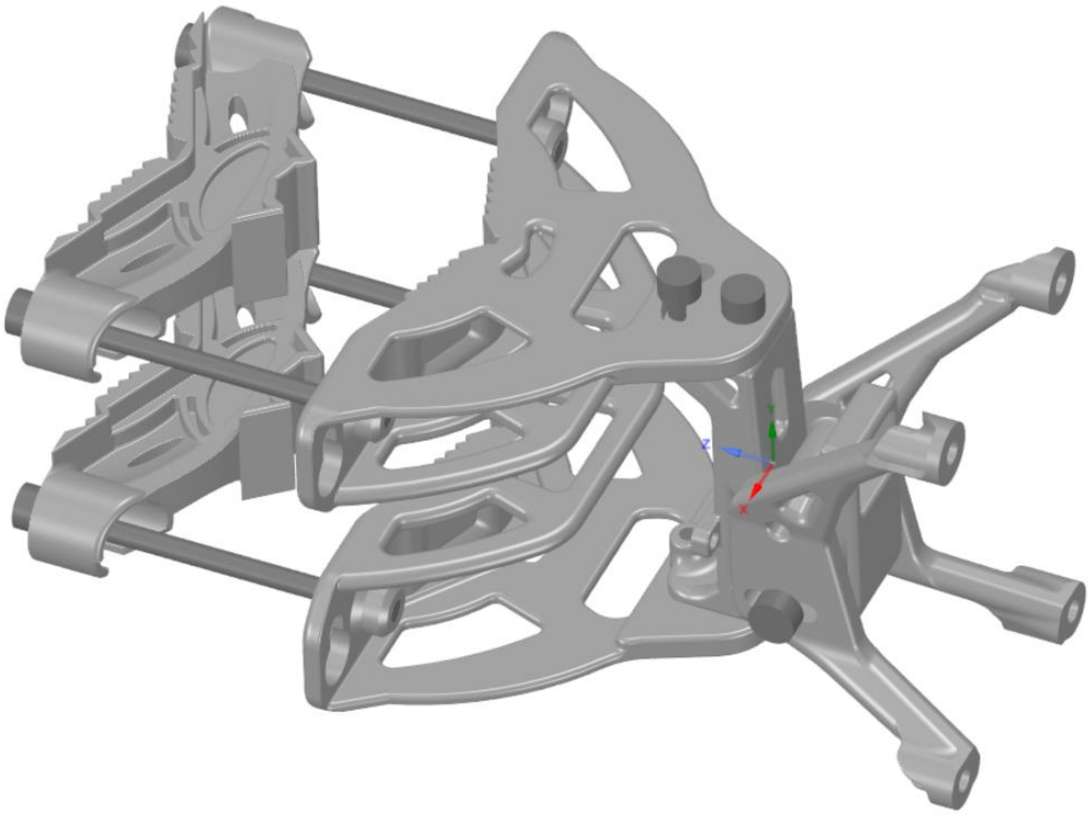


Figure 57. Finalized design of version 3.

A conventional design process for new parts can take up to nine months. For me, the first version came to its final form in about one month. The second version was developed in two weeks and the third version in three days. The first and second versions have quite significant differences, but the second and third not so much.

The current solution for 40Kg products weighs 5,7Kg and is made from stainless steel and aluminium, whereas my design for 40Kg weighs 3,7kg and is made entirely from aluminium. In short, I was able to drop product weight by 45% and change material to be only aluminium. For the 25Kg design there is nothing to compare it to but version 3. weighs 2,5Kg which is very light when taking into consideration what attachments it supports and how much weight it can carry.

7.4.1 Testing the designed product for R&D

Design version 3. was manufactured by AM and tested in in-house facilities. Testing included a vibration test with 25Kg mass in 60mm diameter pole and usability tests.

Result for vibration in 60mm diameter pole was pass. The vibration tests include random vibration, sinusoidal wave vibration and shock. Results also showed that my design was stiffer than one of the current designs that weighs 5,5Kg.

Figure 58. Version 3. design in 30mm diameter pole.

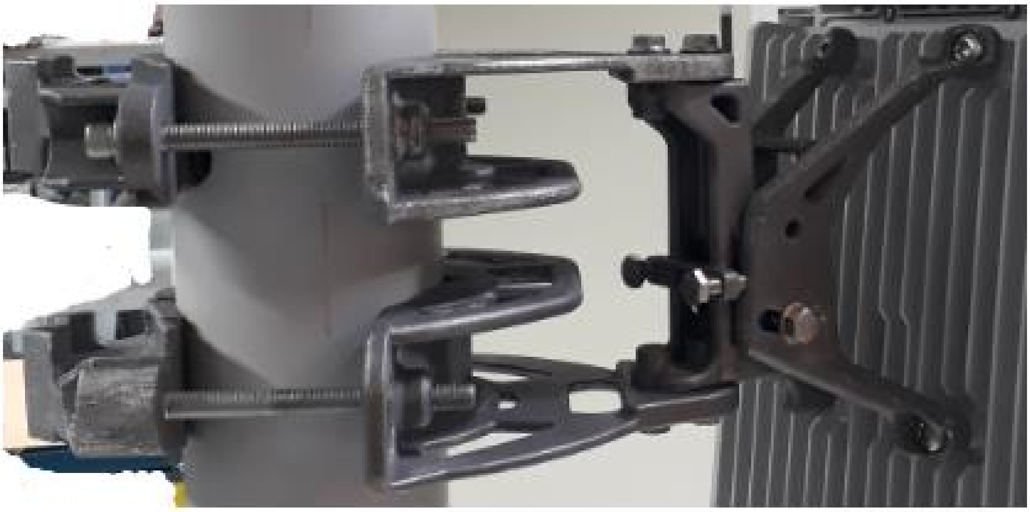


Figure 59. Version 3. design in 60mm diameter pole.

7.5 Implementation

To fully take advantage of the possibilities that TO provides, it must be implemented properly. During my own learning and research phase I gained good experience on what it takes to learn to use the software efficiently and how to benefit from it most efficiently.

TO should be a mandatory part of every mechanical product development or CR/QI projects. To achieve this level of usage, every mechanics designer should be able to use the basic tools for TO. That level of competence, in my opinion, is best cumulated by combining classroom training bought from the service provider and online trainings one can do from their own home.

As the subject of TO plus simulating is very broad, it would make sense to me to have so called “key users” who will be further trained than everyone else. These key users would then act as on-site professionals. By my experience it can sometimes take days to find what the issue is if you don’t have any idea what it could be, but by asking the issue could have been resolved within minutes.

Then, after the staff is trained on how to use the software, the next step is to implement it into the process. In this thesis I have presented process charts for R&D and PM that utilize TO as it should be utilized.

The new presented process flow should be taken into use gradually over some years. The first projects it should be adopted for are weight sensitive projects for R&D and large volumes products CR/QI projects for PM. These are the kind of projects that show the benefits of TO most clearly, and therefore the success of these projects might lessen the resistance to change. Research shows that it is of utmost importance to acknowledge the impact of change resistance when trying to implement new policies, processes or tools as it may have a significant financial impact. Also, in general, long phase in, phase out times cause problems since at that time, many different processes may be in use, and that can create overall confusion. (Grama, Todericiu 2016)

8 SUMMARY/DISCUSSION

Topology optimization has been around for decades but only recently computers have gained enough computing power for it to be effectively used. This combined with AM technology advancement that have happened in recent years makes topology optimization very interesting and current topic when discussing the development of mechanical products. This thesis researched how topology optimization could be applied to product maintenance and R&D organizations. I set two research questions to help guide the research and work. Below there are the questions and brief answers to them based on my research. Results and more extensive answers to the questions in detail can be found from chapters 4 to 7.

RQ 1. How can topology optimization be applied to PM?

To take full advantage of TO in PM, it should be implemented in all cost reduction/quality improvement projects. Learning curve with TO isn't too steep so it is possible to teach the basics to every mechanical engineer that works in product maintenance. Most savings will cumulate from high volume products so if it's possible the implementation of TO should start from high volume products.

RQ 2. How can TO be applied to R&D?

TO adds most value to the organization if it is applied to the product development process as early as possible. This in theory cuts cost and lead time most and that claim is backed by the results gained from pilot studies. TO should be a mandatory step in every load bearing product development project. Best possible situation would be if TO would be a tool that every mechanical R&D engineer could use.

Topology optimization has many benefits that I recognized during my research and while developing demo products. Next, I will list the benefits and why topology optimization should be used.

- Topology optimized mechanics can help reach part/product weight target.

- In the future AM will become more affordable, combining TO with AM results in best possible weight performance ratio

- Optimization leads to better quality and performance (i.e. more evenly distributed loading) of mechanical products

- It is possible to reach savings in logistics cost; lighter, smaller parts -> less logistics costs

- With TO, especially when combined with AM, it is possible to reduce part count -> increased usability, fewer parts to maintain

- Fewer parts or smaller and lighter parts -> Less tooling costs with casted parts

- With optimizing, new material possibilities may be discovered, for example plastic instead of aluminium -> less tooling cost and less raw material cost, less weight

- Topology optimizing accelerates the product development process -> less product development cost, faster phase in, phase out

- Faster phase in, phase out process -> Implement new products or cost savings faster

As can be seen from the list, most benefits revolve around decreasing weight. My research suggests that it is possible to lower part weight by at least 30% with TO compared to traditional designing. There can, of course, be some differences between different kinds of products. I would say that most benefit can be gained from topology optimization when the product must withstand forces in different directions and when the points where the forces act are far from each other. In some cases, topology optimization can also suggest which fixing points should be used for the optimal structure. Creating geometry for products that have forces acting on different directions and on various planes is difficult and cumbersome. While it is worth mentioning that a good mechanical designer engineer can optimize certain structures almost as well as TO, it does not help since the design can be suboptimal at the beginning. Because of this, TO should be used in the very early stages of the NPD process. TO could bring clarity to the so-called fuzzy start of designing.

Topology optimization does have some drawbacks. First, licenses needed for performing TO and simulations cost quite much. Second is that it requires significant amount of computing power and memory from your computer. Server clusters can be used to speed up the calculation but that increases the license costs. Therefore it is feasible to say that small businesses might have some issues with the cost of using TO and simulation raising too high compared to the savings it can bring. For large and medium-sized companies, the cost of licenses and computing power should not be an issue when compared to the possible cost savings cumulated.

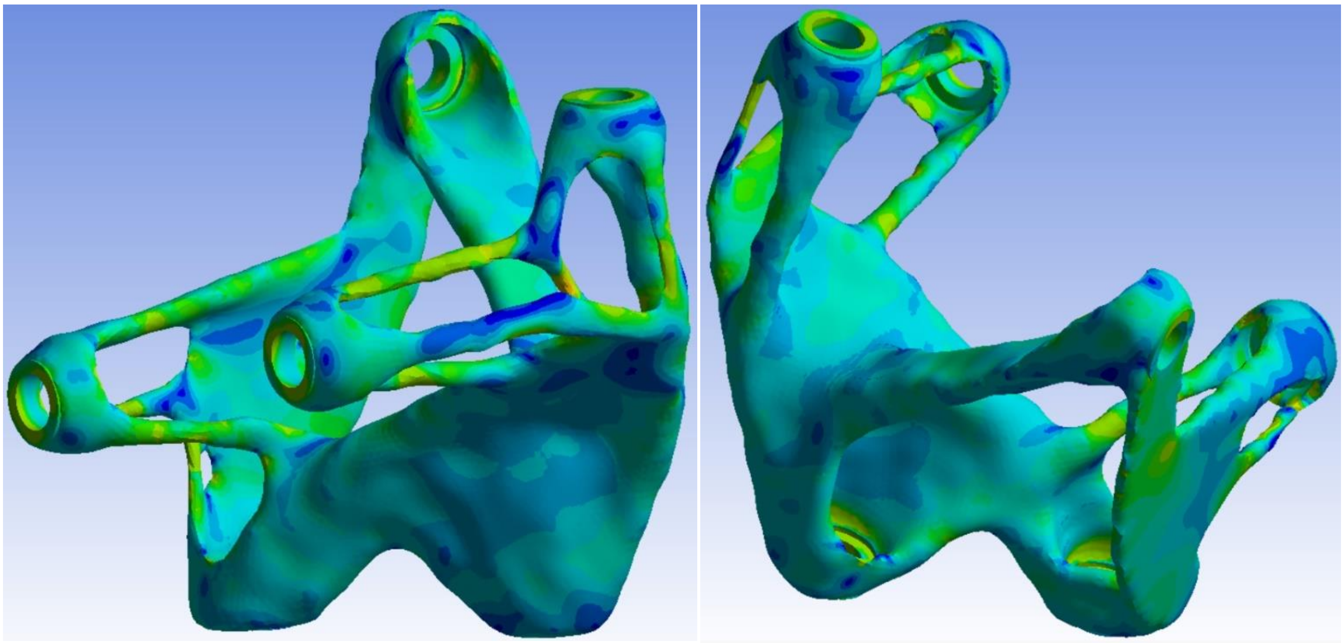


Figure 60. Example of optimal use case for topology optimization, the part in the picture weights 1,22Kg and is made of AlSi10Mg, but it can withstand over 400Kg pull force from each of the four holes seen in the upper half. The part is fixed from the two holes at the bottom.

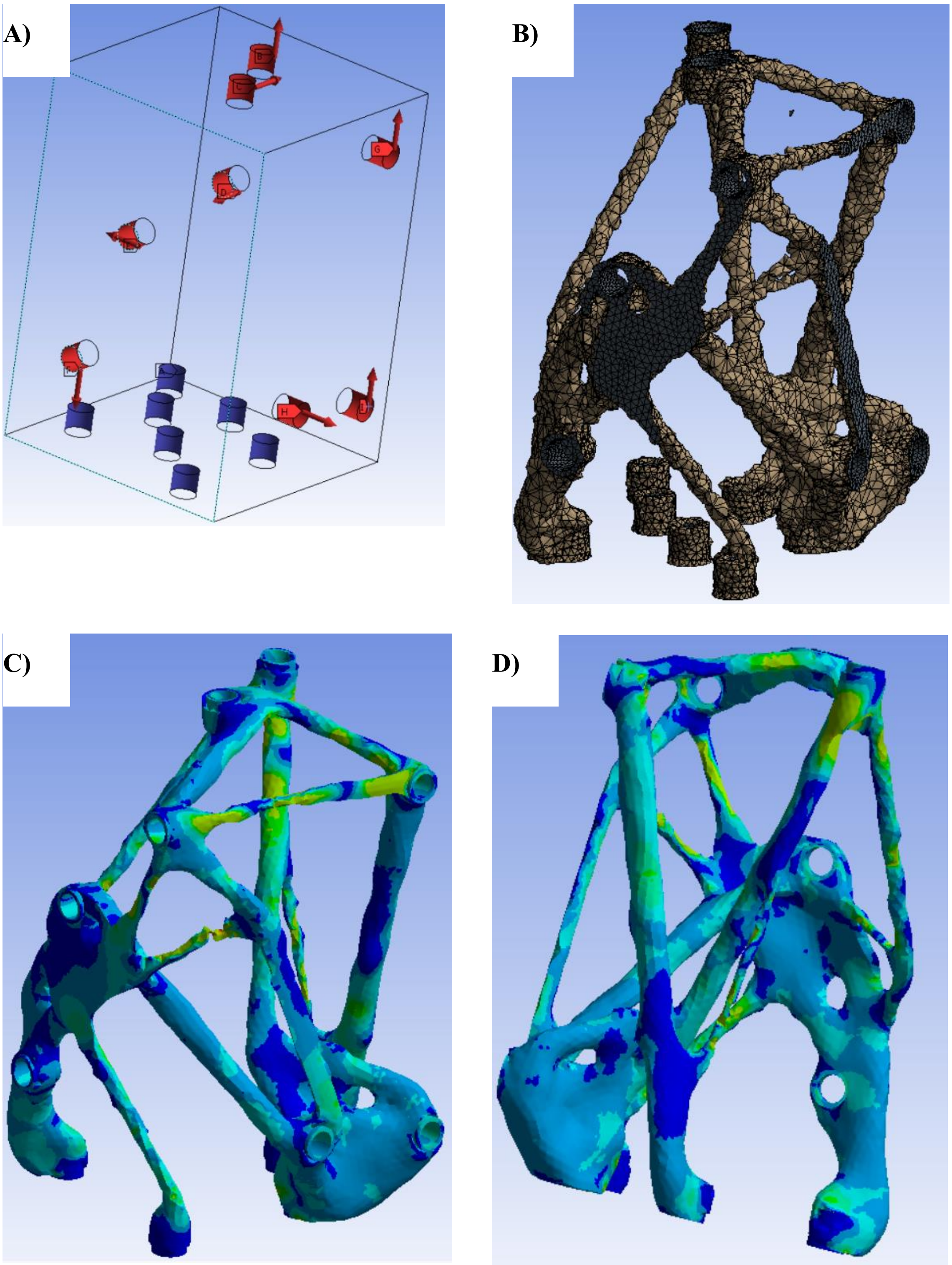


Figure 61. Example of optimization where TO gives a suggestion on which fixing point should be used. A) Design space with applied forces (red) and supports (blue), B) Result of topology optimization, C)/D) Prototype design under stress.

When I started work on this thesis, I had no previous experience in designing mechanical products, let alone in TO or simulating. The learning curve for TO and simulating is exponential, it is easy to get started but more complex optimizing cases or simulations require much more learning and studying. This is especially true with simulating, as basic simulations are easy to perform but more complex ones require exponentially more knowledge and time.

I see that in the close future such tools as topology optimization and advanced simulation tools will became much more common. It is also apparent that AM will be more common as a production method as it keeps getting down towards a more reasonable price. In addition, the goal is at some point to move completely to a virtual environment, which would mean that all product development would happen in simulated surroundings. Virtual environment could bring needed speed and flexibility to product development. In a perfect system, different simulations could be combined to create a perfect replica of actual used case. Virtual product development would also render the need for physical samples to zero.

Topology optimizing software can considered to be a computer-generated design software. In the future other software that can generate designs based on given parameters will emerge. But based on what I have learned, the need for engineers and designers will remain.

Next thing to research regarding topology optimization would be figuring out how to utilize it for optimizing product heat transfer. There could be a possibility to utilize heat transfer elements to create structural integrity and better their heat transferring capabilities, all at once. That could be feasible when using AM as production method.

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